# DEVELOPMENT OF A COMPUTER MODEL TO PREDICT OVERHEATING IN PASSIVE SOLAR HOUSES

RENEWABLE ENERGY BRANCH

PREPARED FOR:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Canada
DSS Contract File No.: 48SZ 23216-6-6255
May 29, 1987

PREPARED BY:

G. K. Yuill and Associates Ltd.
1441 Pembina Highway
WINNIPEG, Manitoba
R3T 2C4
(204) 474-2461
File: 6188,DD#55

SCIENTIFIC AUTHORITY:

Mr. Timothy Mayo
Passive Solar Technology Coordinator
Energy, Mines and Resources Canada
460 O'Connor Street, 4th Floor
Ottawa, Ontario
K1A 0E4

# TABLE OF CONTENTS


| | | |
|---|---|---|
| | PREFACE | i |
| | ABSTRACT | ii |
| | EXECUTIVE SUMMARY | iii |
| 1.0 | INTRODUCTION | 1 |
| 2.0 | THE OVERHEATING MODEL | 3 |
| 2.1 | The Model | 4 |
| 2.2 | The Results | 5 |
| 2.3 | Discussion | 16 |
| 3.0 | WES SHADING MODEL | 25 |
| 3.1 | Introduction | 25 |
| 3.2 | Objectives | 25 |
| 3.3 | Method | 26 |
| | 3.3.1 Determination of Shading Factor $F_S$ | 26 |
| 3.4 | Results | 29 |
| 3.5 | Discussion | 30 |
| | REFERENCES | 42 |
| | APPENDIX | |

## LIST OF TABLES


| | | |
|---|---|---|
| Table 2.1 | Cooling Load: HBH vs. Daily Models | 17 |
| Table 2.2 | Cooling Load: BLAST, Daily and HBH Model | 22 |
| Table 2.3 | Cooling System On-time: BLAST vs. HBH Model | 22 |
| Table 3.1 | Curve Fit Numbers for the Effect of Window Overhang on Incident Solar Radiation on South Vertical Windows | 31 |
| Table 3.2 | Curve Fit Numbers for the Effect of Window Overhang on Incident Solar Radiation on East Vertical Windows | 32 |
| Table 3.3 | Comparison of $F_s$ Computed Using Hourly Weather Data and $F_s$ Calculated from the WES Shading Model Correlations (for East Window) | 33 |


## LIST OF FIGURES


| | | |
|---|---|---|
| Figure 2.1 | Average Day Temperature Fluctuation | 6 |
| Figure 2.2 | Amplitude vs. Delta Standard Deviation | 8 |
| Figure 2.3(a,b) | $T_{be}$ and $DH_c$ | 11 |
| Figure 2.4 | $Q_{nm}/Q_m$ vs. the Mass Utilization Factor F | 14 |
| Figure 2.5/2.6 | Monthly Cooling, HBH and Daily Models | 18-19 |
| Figure 2.7/2.8 | Cooling Load, Daily and HBH Models | 20-21 |
| Figure 2.9 | Cooling Load, BLAST, Daily and HBH Models | 23 |
| Figure 2.10 | Hours of Cooling, BLAST, HBH Models | 24 |
| Figure 3.1(a,b) | Negative Separation Ratio | 35 |
| Figure 3.2(a,b) | Positive Separation Ratio | 36 |
| Figure 3.3(a,b) | South Window Incident Radiation | 37 |
| Figure 3.3(c,d) | Shading Factor $F_s$, WES and Balcomb Model | 38 |
| Figure 3.4(a-f) | East Window Incident Radiation | 39-41 |

## Disclaimer

"This report is distributed for informational purposes only and does not necessarily reflect the views of the Government of Canada nor constitute an endorsement of any commercial product or person. Neither Canada nor its ministers, officers, employees or agents makes any warranty in respect of this report or assumes any liability arising out of this report."

## PREFACE

The following is a research report outlining the development of a technique to determine potential overheating in passive solar houses. It was developed for inclusion in the HOT-2000 program. With this technique, passive solar home designs can be improved to reduce summer overheating.

This technique is considerably faster to perform than an hourly heat balance, while being more accurate than calculations based solely on monthly mean data. Sensitivity to thermal mass is also included, to greatly increase the model's accuracy.

This technique was developed by comparison with a simple lumped capacitance hour-by-hour heat balance model. To verify accuracy, both the new technique and the hour-by-hour model were tested against the BLAST computer program. Good results were obtained.

HOT-2000 was originally developed as a program to determine winter heating loads, so the algorithm to determine solar shading is primarily designed for winter conditions. An improved shading model is presented that can be used for both summer and winter conditions, making the overheating model more useful to calculate summer overheating within HOT-2000.

## ABSTRACT

A simple technique to calculate the monthly degree of overheating for a building from monthly average data has been developed. Overheating has been defined as the energy required per unit area to maintain a building below a specified temperature. Overheating for realistic building models was calculated by finding overheating for zero thermal mass buildings, and using a utilization factor to determine the effect of thermal mass on overheating. This utilization factor was related to the available energy for cooling stored in the mass and to the zero thermal mass cooling loads. A simple lumped capacitance hour-by-hour heat balance model was used to develop correlations for the utilization factor. Agreement between the hour-by-hour model and the model developed was excellent, with approximately 5% error.

Comparison of the above models was made with BLAST, a complex hourly building load analysis program. Agreement was very good, with an average error for the daily model in the order of 10%, and an RMS deviation of 15.6 kWh/month.

A shading model has been developed to improve the suitability of the overheating model for inclusion in HOTCAN. Calculation of shading on the east and west sides of a building, as well as shading by overhangs that extend below the top of a window, such as awnings has been added. Comparison of this model for south side shading to the Balcomb model used in HOTCAN show good agreement, with the largest deviation 5.7%, and an RMS deviation of 2.2%.

## EXECUTIVE SUMMARY

Passive solar houses designed to maximize winter solar gains may overheat in summer, if poorly designed. In this project, a means of predicting overheating has been developed, so that it can be foreseen and avoided. Overheating has been quantified by the cooling load, the amount of cooling energy needed to maintain a building below a specified temperature, per unit floor area. This does not imply that the building would have a cooling system. It is assumed that the amount of discomfort experienced by a person in the building is proportional to the amount of heat that would have to be removed from the building to maintain comfort. A technique to determine this overheating, using monthly average data has been developed, and compares favorably with BLAST, a much more sophisticated hourly heat balance simulation.

This technique is an extension of an earlier project. The original intent of this project was to add thermal mass sensitivity to the technique, but in doing so, the model underwent significant changes that vastly improved the accuracy of the model.

The overheating model was originally proposed as a possible inclusion in the HOT-2000 computer program, which does not currently have a cooling load model. To improve the suitability of this model for HOT-2000, an improved window shading model was developed that is better able to model overhangs that reduce summer overheating, specifically overhangs on the west and east sides of the house, and overhangs that extend below the top of the window, such as awnings. The current shading model in HOT-2000 does not permit these shadings, as it was intended for shading in winter conditions.

Due to the time coincidence of high solar gains and relatively high ambient temperatures during the daytime, cooling loads occur for only a portion of the day. This time concentration makes the calculation of cooling load from mean monthly data impossible.

The time concentration difficulty would not be a problem if an hourly heat balance were performed on the house, but this approach requires a good deal of computational time. As well, a large amount of weather data would be required for each location.

As a compromise, an hourly variation in ambient temperature was generated for a typical day in a month. Temperatures during a month at each particular hour of the day would be statistically distributed about the mean temperature for that hour. Hourly values of the building solar gains can be found for a typical day from monthly average solar data. If the internal gains and ground losses can be determined for a month, then the balance point temperature can be found for each hour of the day. The cooling degree days and the number of hours above the balance point temperature for each hour of the day can be determined from the statistical distribution of temperature for that hour. The cooling load for each hour can then be found.

The above method assumes a building with no thermal mass. Passive solar houses have a wide range of thermal masses but the mass is never zero. The actual cooling load for a house will be below the above value since the house mass will have thermal inertia. A simple lumped capacitance hour-by-hour heat balance model was used to develop a relation for a thermal mass utilization factor for cooling energy stored by the mass.

Agreement for the model developed and the hour-by-hour model was excellent, with typical errors of 5%.

A BLAST analysis was carried out for verification of the model. Agreement for cooling load was good, with errors in the order of 10%, and an RMS deviation of 15.6 kWh per month.

Agreement between BLAST and the model developed was good, though only one comparison was made because of both time and budgetary constraints. Although there is no reason to believe agreement with BLAST would be substantially poorer, more BLAST comparisons should be made to further reinforce the credibility of this model.

A shading model has been developed from correlations of the results of an hour-by-hour analysis of shading. It has been compared to a more sophisticated model for south shadings, and agreement was good, with a largest error of about 5.7%, or an RMS deviation of 2.2%.

## 1.0 INTRODUCTION

A passive solar house is designed to optimize solar gains during winter months to offset the space heating load. Unfortunately, measures taken to increase winter solar gains may cause excessive summer solar gains, causing overheating.

Overheating can be quantified as the cooling load per unit of floor area for a house. By doing this, overheating levels can be compared for any size or type of house. Overheating has been defined in this way in the present study, since the cooling load is an easily quantifiable means of determining overheating. This does not suggest that the house in question will have a cooling system. Rather, it is assumed that the total amount of discomfort experienced by an occupant due to overheating is proportional to the amount of heat which would have to be removed to keep it comfortable.

The estimation of cooling load for a house is more difficult than that of heating load, given only monthly average data. Particularly in Canadian climates, heating is constantly required throughout the entire day in some winter months. In summer months, cooling is usually required only for a portion of the day, and the periods when the cooling system is operating is highly dependent on the amount and time coincidence of solar gains, outdoor temperature, and internal gains.

A model has been developed to calculate overheating, taking into account gain levels and time coincidence of these gains. It has the capability to calculate this overheating for any thermal mass level. This is important from the standpoint of passive solar houses, as a wide range of thermal mass levels can be found. This model is described in Section 2.

This model has developed as a possible addition to the HOT-2000 energy analysis program, which uses the HOTCAN model for shading of windows by overhangs. HOT-2000 was originally intended to be used primarily to calculate winter heating loads. One of the primary

elements in calculating these loads is the amount of solar gains, and in winter most of these loads occur through south-facing windows. Shading of the east and west windows play insignificant roles in reducing solar gains, since the sun is so low in the sky in winter. For this reason, HOT-2000 has an algorithm for estimating shading effects of overhangs on south-facing windows, but not on east or west-facing windows. It also has no provision for modeling overhangs which extend below the top of the window, such as awnings.

These deficiencies do not create a problem when only net winter heating loads are calculated, but they cause a difficulty when summer cooling loads are to be analyzed. In the summer, there are substantial solar gains through east and west windows so shading by overhangs is desirable. Awnings are also a common means of reducing solar gains, so it is also necessary that they can be modeled.

A shading model has been developed to determine shading effects for the above cases. It is described in section 3. A comparison of the predictions of this model to those of a more sophisticated model is also presented.

## 2.0 THE OVERHEATING MODEL: INTRODUCTION

In the initial attempts to develop the overheating model, the Erbs, Klein and Beckman (EKB) (Ref. 1) method of generating monthly degree days from any base temperature was used. This method uses monthly mean temperature and monthly standard deviation of temperature to generate a statistical distribution of outdoor temperature over a month. Degree days for any base temperature could then be found by integration of the statistical distribution. Multiplication of the degree days with an overall heat gain coefficient would give the conduction and infiltration heat gain for the month.

The same reference has an equation to calculate the number of hours above any base temperature for a month. These hours are multiplied by the average ground losses and solar and internal gains to find the total monthly gains. The net cooling load should be the sum of the conduction heat gains and the total gains.

Calculation of cooling load by this method is inaccurate, for three major reasons. The first is that the solar and internal gains can easily be large enough to create significant cooling loads when the conduction gains are negative. The second and most significant reason is that the solar and internal gains are distributed throughout the day in a non-uniform way, so that using the number of hours above a base temperature and the monthly average gains does not accurately estimate the contribution of gains to cooling load. A related problem is that it would be impossible to find the time coincidence of the higher solar gains found at midday with the higher ambient temperatures that accompany them. Thirdly, the effect of thermal mass in absorbing heat during cooling hours and releasing it during other periods is not accounted for.

A model is described here which solves all of these problems. This model uses a different method of describing the statistical distribution of ambient temperature, although it still uses monthly average data. An average day for a month is described by a periodic

function. The ambient temperature during each hour is then statistically distributed about the point for that hour on the average day function. A heat balance for each hour of the day can be performed if the average solar gains and internal gains are considered constant over the month for that hour. In this way, the time variation and time coincidence of gains can be accounted for. To avoid confusion, this technique is called the "daily" model, as opposed to the "monthly" model which incorporates the EKB temperature model.

A simple hour-by-hour (or "hourly") model was developed to determine the effect of thermal mass on cooling load. It uses a heat balance performed hourly over an entire month on a single lumped mass with an exponential temperature response to gains. Several runs of this model were made with varying effective R-values, at different locations for four different mass levels. A factor was found that relates the change in cooling load because of thermal mass to the auxiliary heat or cooling input required to maintain a temperature range for a massless building.

The incorporation of an equation to find the mass utilization factor into the daily model resulted in a cooling load model that compared very favorably with the hour-by-hour calculation. This model compares with more sophisticated models with reasonable accuracy.

## 2.1 The Overheating Model

The hourly outdoor temperature variation of an average day has been described by Erbs et al. (Ref. 1) as

$$[(\overline{T}_h - \overline{T}_m)/A] = 0.4632 \cos(t^* - 3.805) + 0.0984 \cos(2t^* - 0.360) + 0.0168 \cos(3t^* - 0.822) + 0.0138 \cos(4t^* - 3.513) \quad (2.1)$$

where $T_h$ = average temperature for hour, °C
$T_m$ = monthly average temperature, °C
A = amplitude of temperature variation throughout the day, peak to peak, °C
t* = hour variable, degrees

The hour variable t* is given by

$$t^* = 2\pi(t-1)/24 \qquad (2.2)$$

where t = hour, with 1 corresponding to 1 a.m. and 24 corresponding to midnight

A typical plot of this distribution is in Figure 2.1.

The temperature at each hour is statistically distributed throughout the month, with the mean temperature given by (2.1). The hourly standard deviation of temperature must be determined. This information is not usually available. A complication in determining this value is that the input standard deviation, which is the true monthly standard deviation of long-term weather data, does not have an easily discernible relationship to the true standard deviation of the resulting statistical distribution of equation (2.1). The hourly standard deviation has been found to be a function of the monthly standard deviation $\sigma_m$ and the amplitude of temperature variation throughout the day, found by taking the difference between the monthly mean high and low temperature. To determine this function, a number of data points were found for different amplitudes and monthly standard deviations. A characteristic curve was fitted to these points. Data points were obtained by iterating the hourly standard deviation until the true standard deviation of equation (2.1) matched that of the EKB distribution. The hourly standard deviation was fitted to

$$\sigma_h = \sigma_m - \Delta\sigma \qquad (2.3a)$$

and

$$= (0.013/\sigma^2 m)A^3 \qquad (2.3b)$$

where $\sigma_h$ = hourly standard deviation, °C

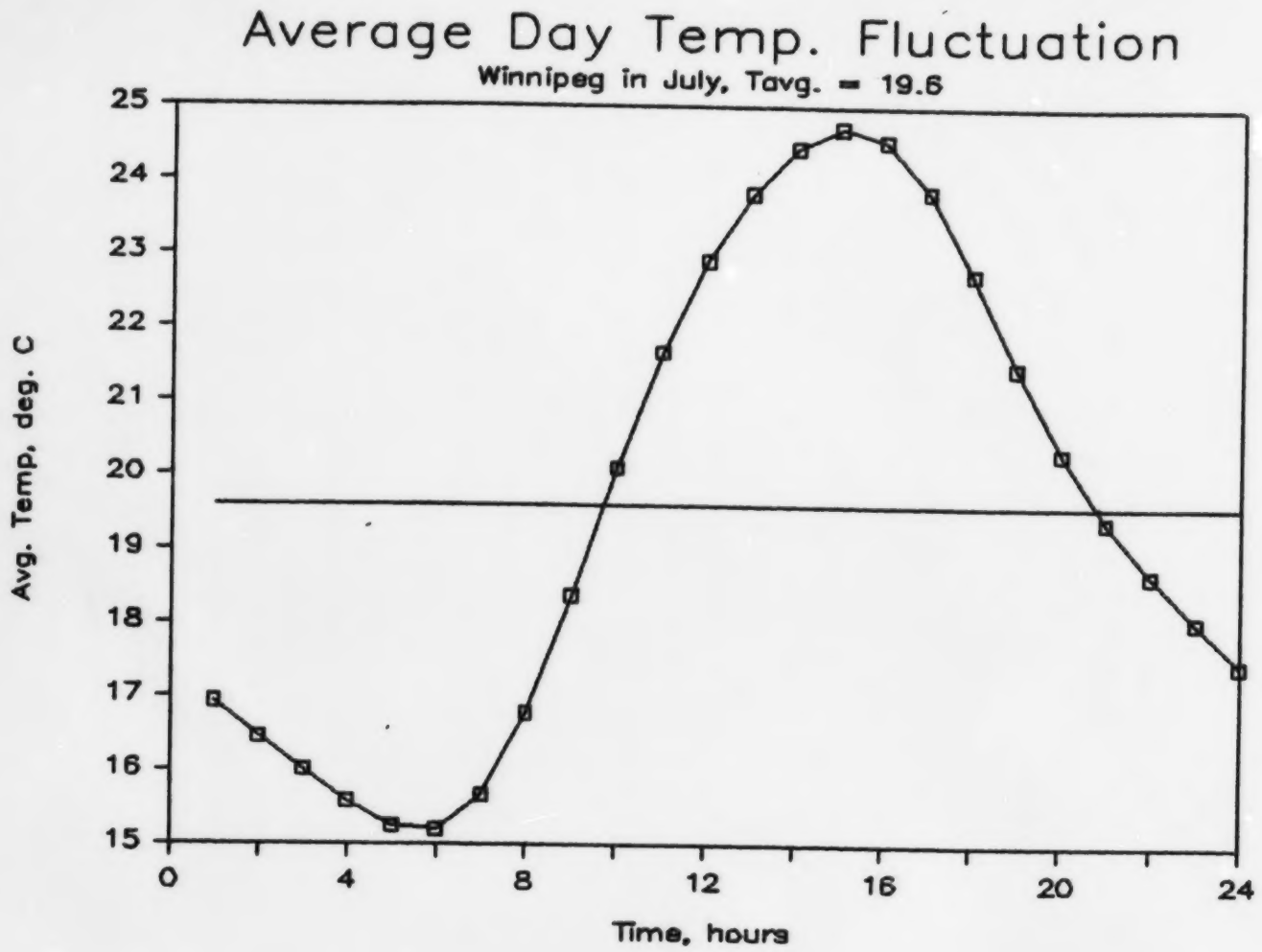



Figure 2.1 The temperature fluctuation for an average day of the month.

$\sigma_m$ = monthly standard deviation, °C
$\Delta\sigma$ = delta standard deviation, °C
A = peak-to-peak amplitude of temperature variation, °C

Curves for $\Delta\sigma$ for different monthly standard deviations can be found in Figure 2.2. If the calculated hourly standard deviation is below zero, then it is set to zero as the best approximation.

The total number of degree hours for the month for a particular hour is (Ref. 1)

$$DH_h = \sigma_h \left(\frac{N}{24}\right)^{3/2} \left[ \frac{h}{2} + \frac{\left\{ \ln \frac{(e^{-1.698h} + e^{1.698h})}{2} \right\}}{3.396} + 0.2041 \right] \quad (2.4)$$

where $DH_h$ = degree hours for the month for a particular hour, °C-h
$\sigma_h$ = hourly standard deviation, °C
N = number of hours in the month
h = normalizing variable

The normalizing variable h is defined by:

for heating $h = (T_b - T_h)/[\sigma_h(N/24)^{0.5}]$ (2.5a)
for cooling $h = (T_h - T_b)/[\sigma_h(N/24)^{0.5}]$ (2.5b)

where $T_b$ = base temperature for heating or cooling
$T_h$ = mean temperature for hour.

The number of hours of cooling is given by

$$N_c = N_D[1 - (1/(1 + \exp(-3.396h))] \quad (2.6)$$

where $N_c$ = number of hours of cooling for the month for a particular hour
$N_D$ = number of days in the month
$h$ = normalizing variable as defined in equations (2.5a) and (2.5b)

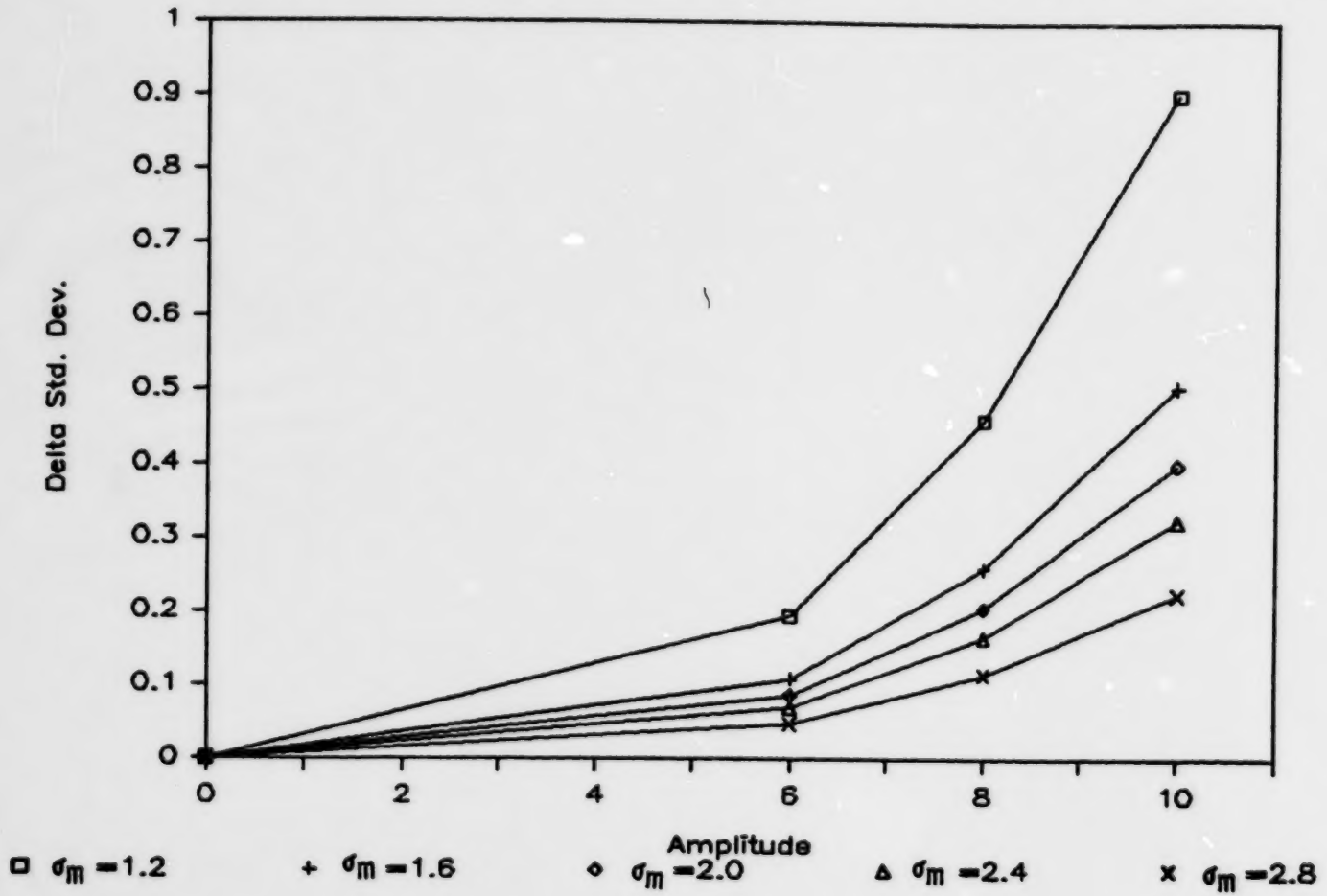



Figure 2.2 Fitted curves to relate amplitude and monthly standard deviation to delta standard deviation.

For a particular hour, the solar and internal gains and ground losses are assumed to be constant throughout the month. The break-even temperature (also known as balance-point temperature) is defined as the temperature at which the total gains, the sum of solar, internal and ground loss gains, are equal to the conduction and infiltration losses. It can be calculated for a particular hour by

$$T_{be} = T_c - [(\overline{S}_h + \overline{I}_h - \overline{G}_h)/(UA + Q\rho Cp)] \qquad (2.7)$$

where $T_{be}$ = building break-even temperature, °C
$T_C$ = cooling setpoint temperature, °C
$\overline{S}_h$ = average solar gains for a particular hour of the day, W
$\overline{I}_h$ = average internal gains for a particular hour, W
$\overline{G}_h$ = average below-grade losses for a particular hour, W
$(UA+Q\rho Cp)$ = the net above-grade heat transfer coefficient, incorporating conduction and infiltration losses, W/°K

Values of $S_h$, the mean solar gains in a hour, can be found by determining the solar radiation on each of the surfaces of the house on an hourly basis. This can be done by translating the mean daily global radiation on a horizontal surface, which is readily available from Environment Canada Atmospheric Environment Service long-range data (Ref. 7). The technique used to do this can be found in Reference 8. Beam and diffuse components of the radiation on the surfaces of the house are found, and the total mean hourly solar gain can be calculated from the house properties.

Values of $I_h$, the mean value of the internal gains for an hour of the day, are normally specified to provide a realistic profile of daily occupancy and equipment usage. $G_h$, the mean ground losses, are normally almost constant over a particular month and can be therefore considered constant on any particular day. The calculation of $G_h$ can be done by a technique such as the Mitalas model for below-grade heat loss (Ref. 9).

With the above information, the cooling load for a massless building can be determined. The cooling load consists of two components, the transmission losses and the total gains. The calculation of the total gains for a particular hour is readily calculated by

$$G_{TOT,h} = N_c(\overline{S}_h + \overline{I}_h - \overline{G}_h) \qquad (2.8)$$

where $G_{TOT,h}$ = total gains for a particular hour, Wh
$N_c$ = number of hours of cooling, to occur at the hour being considered during the month defined by (2.6), and $T_b = T_{be}$ in equation 2.5b.

The transmission losses component is the product of the cooling degree hours and the net above-grade heat transfer coefficient. The cooling degree hours for a particular hour is given by

if $(T_{be} < T_s)$

$$DH_c = CDH(T_s) - \left\{HDH(T_s) - [HDH(T_{be}) + (N_D - N_c(T_{be}))*(T_s - T_{be})]\right\} \qquad (2.9a)$$

if $(T_{be} > T_s)$

$$DH_c = CDH(T_{be}) + [N_c(T_{be}) * (T_{be} - T_s)] \qquad (2.9b)$$

where $DH_c$ = cooling degree hours, °C-hrs

and the other quantities are to base temperatures $T_s$ or $T_{be}$. See Figures 2.3(a) and (b) to illustrate this point further.

The cooling load for the month would be

$$Q_{nm} = \sum_{n=1}^{24} (DHC_n\ (UA + Q\rho Cp) + G_{TOT,n}) \qquad (2.10)$$

where $Q_{nm}$ = monthly no mass cooling load, Wh
$n$ = hour of day.

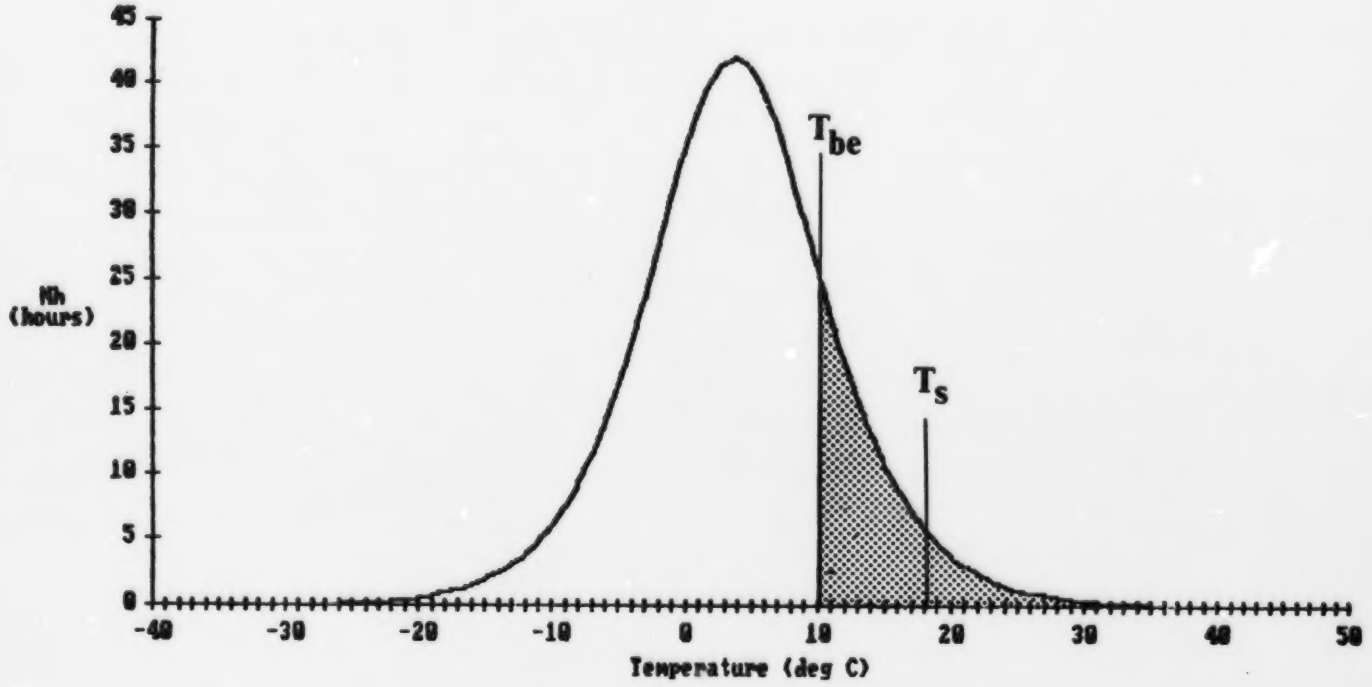



Figure 2.3(a) $DH_c$ area, $T_{be}$ $T_s$

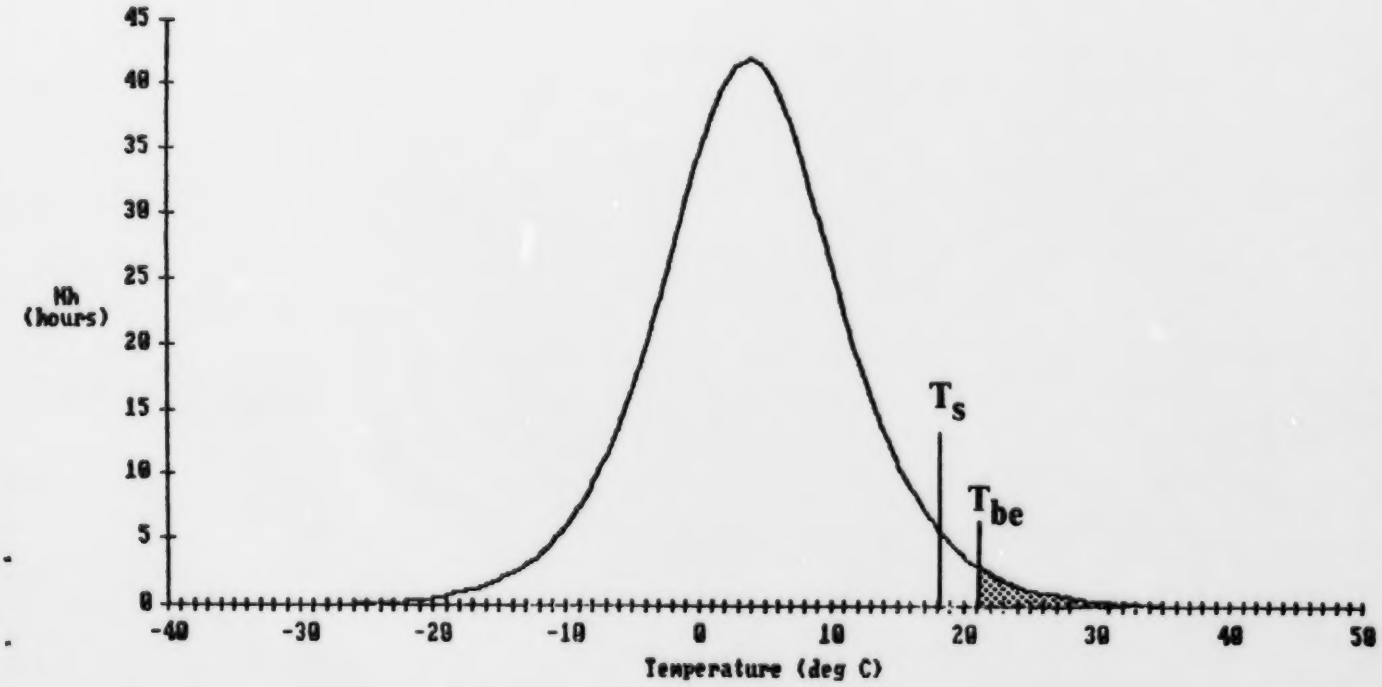



Figure 2.3(b) $DH_c$ area, $T_{be}$ $T_s$

This cooling load is the energy that would be required to maintain a massless building with a large cooling capacity below a specified temperature. While there may appear to be a large number of equations to calculate, the computational time is actually quite small, taking about five seconds per month on an IBM PC XT with a math coprocessor chip installed.

A reduction in cooling load will occur with increasing building thermal mass levels. This occurs because a portion of the energy input to the mass will be absorbed and released at a later time, offsetting the cooling load. The total energy that can be retained by the mass to offset cooling can be estimated by

$$Q_m = [(mCp * \Delta T * N_c(H_{max} + 1))/3600] \qquad (2.11)$$

where $Q_m$ = energy absorbed by the mass, Wh
$mCp$ = building thermal mass, J/°K
$\Delta T$ = dead band width, or the difference between the heating and cooling setpoints, °C
$N_c(H_{max}+1)$ = second highest value of $N_c$ for the month, hours

The actual reduction in cooling load is usually less than $Q_m$, the total energy available to reduce the cooling load due to thermal mass. This is due to the fact that in any given month, there will always be days in which the total energy available to reduce cooling is more than sufficient to bring the cooling load to zero, resulting in an unutilized portion.

To determine the portion of $Q_m$ that is used, F, the mass utilization factor is introduced. It is the fraction of the total energy available to reduce the cooling load that is actually used. Values of F were calculated by making runs of the hour-by-hour and daily model for several sets of house thermal parameters. F was found by

$$F = [(Q_{nm,d} - Q_{CL,h})/Q_m] \qquad (2.12)$$

where F = mass utilization factor, dimensionless

$Q_{nm,d}$ = cooling load, no mass case, by daily model (Wh)

$Q_{CL,h}$ = cooling load with mass effects, by hour-by-hour model (Wh)

$Q_m$ = available energy that can be used to offset cooling (Wh), from equation (2.11)

The mass utilization factor F can be correlated to the fraction of $Q_m$ that is supplied by an auxiliary energy input. In warmer months, the cooling load is much greater than the heating load $Q_{HL}$ so F is small, ie. the cooling load is not greatly reduced by mass effects. F should increase as the monthly heating load increases up to a limit. The limit is reached when $Q_{HL} = Q_{nm}$, or when the heating load is balanced by the cooling load in the massless case. When the limit is reached, most of the cooling available from the thermal mass will have been exhausted, and F will remain relatively constant with increasing cooling load. F will never reach 1.0, the case when the cooling that is available from the thermal mass is fully utilized to reduce the cooling load, because there will always be days in any given month where full utilization will not occur.

F was correlated to $R_m$, the ratio of auxiliary heat input to $Q_m$, the total cooling energy available from the mass. The input energy fraction $R_m$ is defined by

if $Q_{HL} < Q_{nm}$ then

$$R_m = Q_{HL}/Q_m \tag{2.13a}$$

else

$$R_m = Q_{nm}/Q_m \tag{2.13b}$$

Several runs of an hour-by-hour cooling load model were made to find F, the mass utilization factor by equation (2.12). Runs were made for five major Canadian cities, three different effective UA values and four thermal mass levels. A curve was fitted to $R_m$, and Figure 2.4 shows a scatter plot of this data and the fitted curve.

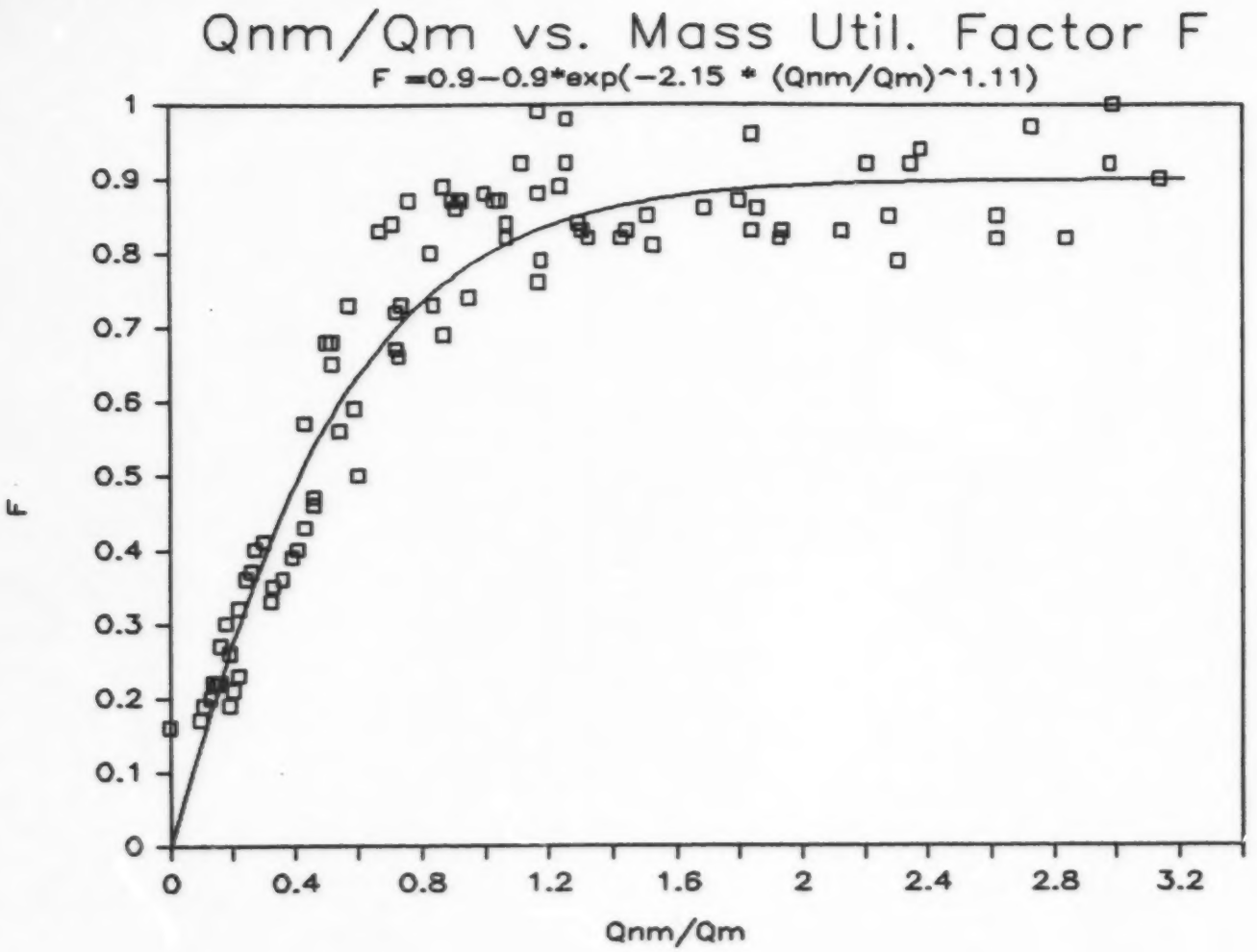



Figure 2.4 $Q_{nm}/Q_m$ vs. the mass utilization factor F.

The mass utilization factor F was fitted to $R_m$ by

$$F = 0.9 - 0.9 \exp(-2.26\ R_m^{1.11}) \qquad (2.14)$$

where F = mass utilization factor, dimensionless

The monthly overheating corrected for the thermal mass can be calculated by

$$Q_{CL} = (Q_{nm} - FQ_m)/A_B \qquad (2.15)$$

where $Q_{CL}$ = monthly cooling load, $Wh/m^2$

$A_B$ = building floor area, $m^2$

## 2.2 Results

The method described above and an hour-by-hour lumped capacitance model were used to find the monthly cooling loads for houses in Montreal, Vancouver, Winnipeg, and St. John's. The results are tabulated in Table 1.1, and plotted in Figures 2.5 to 2.8. The daily model shows excellent agreement with the hour-by-hour heat balance model. Errors are typically in the order of 5%, and the absolute error about 10 kWh per month. This error corresponds to a continuous error of 13.4 W, which is insignificant.

To further test the validity of the daily model, a comparison was made with BLAST, a complex hourly building load analysis program. BLAST has been well verified in the past (Ref. 10) and compares well with measured data.

A house near Edmonton was modeled with BLAST, the daily model and the hour-by-hour model. The cooling load and cooling system on-time were compared. Results can be found in Tables 1.2 and 1.3, and Figures 2.9 and 2.10. Both the daily model and the hour-by-hour model show good agreement with the BLAST model for cooling load. The RMS deviation of the daily model is 15.6 kWh per month from BLAST, or about 21 W on a

continuous basis. Considering that BLAST is a vastly more sophisticated simulation program requiring several minutes to run on a CYBER mainframe, this is an acceptable level of error.

Further BLAST simulations were not attempted due to both budgetary and time constraints, but there is no reason to believe that significant errors will occur in subsequent trials. Further BLAST comparisons would be desirable to further reinforce the validity of the daily cooling load model.

## 2.3 Discussion

$Q_{CL}$ represents the overheating expressed as the cooling load per unit of floor area that a building would require to maintain a specified temperature. It would therefore represent the actual cooling load which would be required for a building if the cooling equipment were sized so that the load required at any time was below the capacity of the building. Therefore it may be used to calculate the cooling energy required if an average Coefficient of Performance (COP) for the cooling equipment is used. It would not be difficult to extend the method to calculate COP as a function of temperature.

Table 2.1

Cooling Load: Daily vs. Hour-by-Hour Models

| City | Montreal | | Vancouver | | Winnipeg | | | | | | St. Johns | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Insulation Level | medium | | medium | | medium | | | | light | | medium | | | |
| Thermal Mass | 4.48 MJ/°K | | 4.48 MJ/°K | | 4.48 MJ/°K | | 11.4 MJ/°K | | 4.48 MJ/°K | | 4.48 MJ/°K | | 11.4 MJ/°K | |
| Month | Daily | HBH | Daily | HBH | Daily | HBH | Daily | HBH | Daily | HBH | Daily | HBH | Daily | HBH |
| 4 | 0 | 0 | 0 | 0 | 1.44 | 17.96 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 68.0 | 72.05 | 60.77 | 70.23 | 109.81 | 100.79 | 0 | 14.36 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 186.57 | 198.68 | 137.84 | 145.20 | 233.50 | 241.32 | 97.57 | 82.95 | 0 | 1.02 | 36.15 | 41.81 | 0 | 0.28 |
| 7 | 364.32 | 340.27 | 281.94 | 290.74 | 402.12 | 409.86 | 246.98 | 261.24 | 109.26 | 119.37 | 178.07 | 183.50 | 50.27 | 45.43 |
| 8 | 296.17 | 300.03 | 281.00 | 284.26 | 379.34 | 384.34 | 225.86 | 226.44 | 115.41 | 125.24 | 159.81 | 159.22 | 37.93 | 41.77 |
| 9 | 171.83 | 168.39 | 157.99 | 163.36 | 159.70 | 163.51 | 9.40 | 18.94 | 0 | 0.41 | N/A | N/A | N/A | N/A |

Cooling loads are expressed in kWh/month

410557

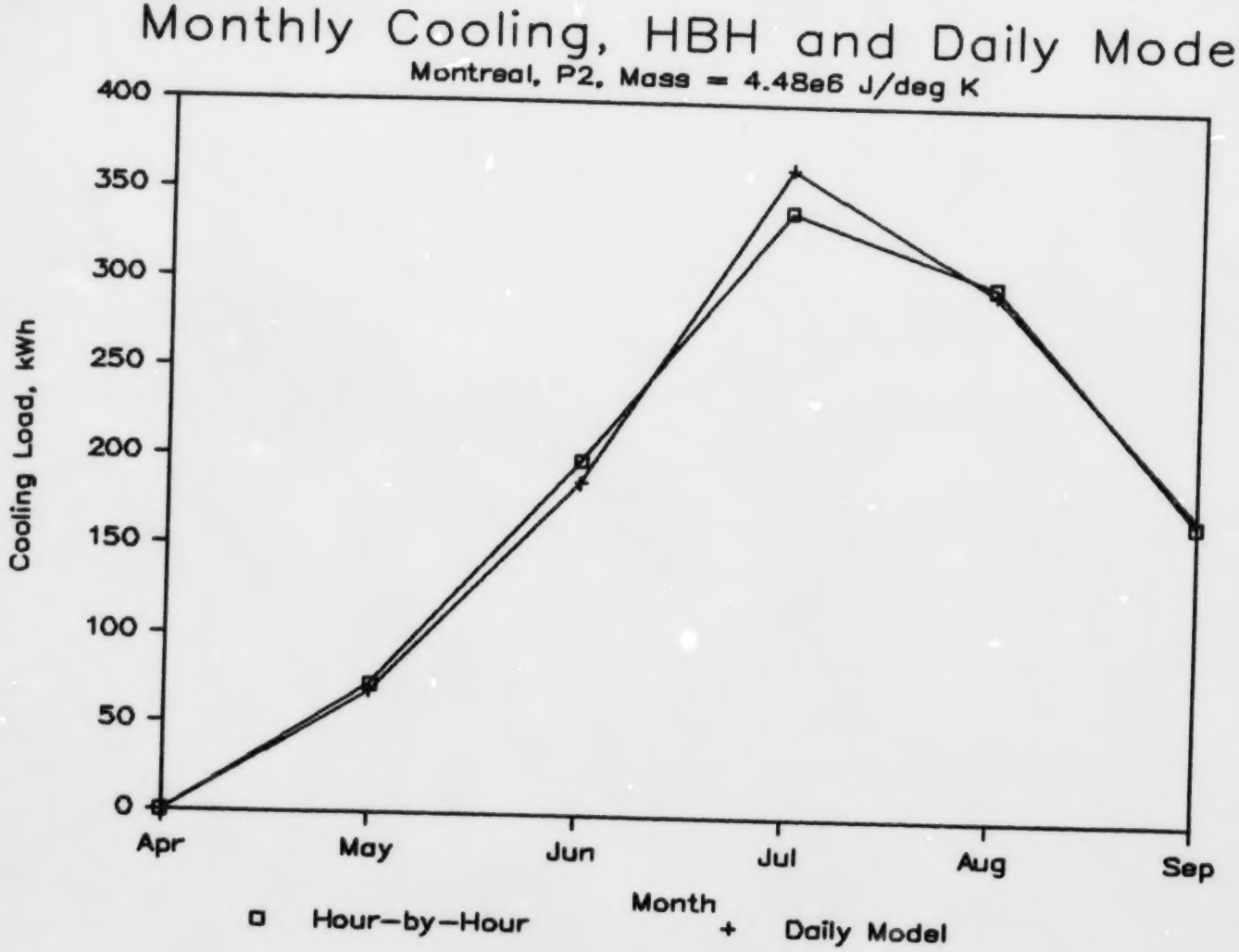



Figure 2.5

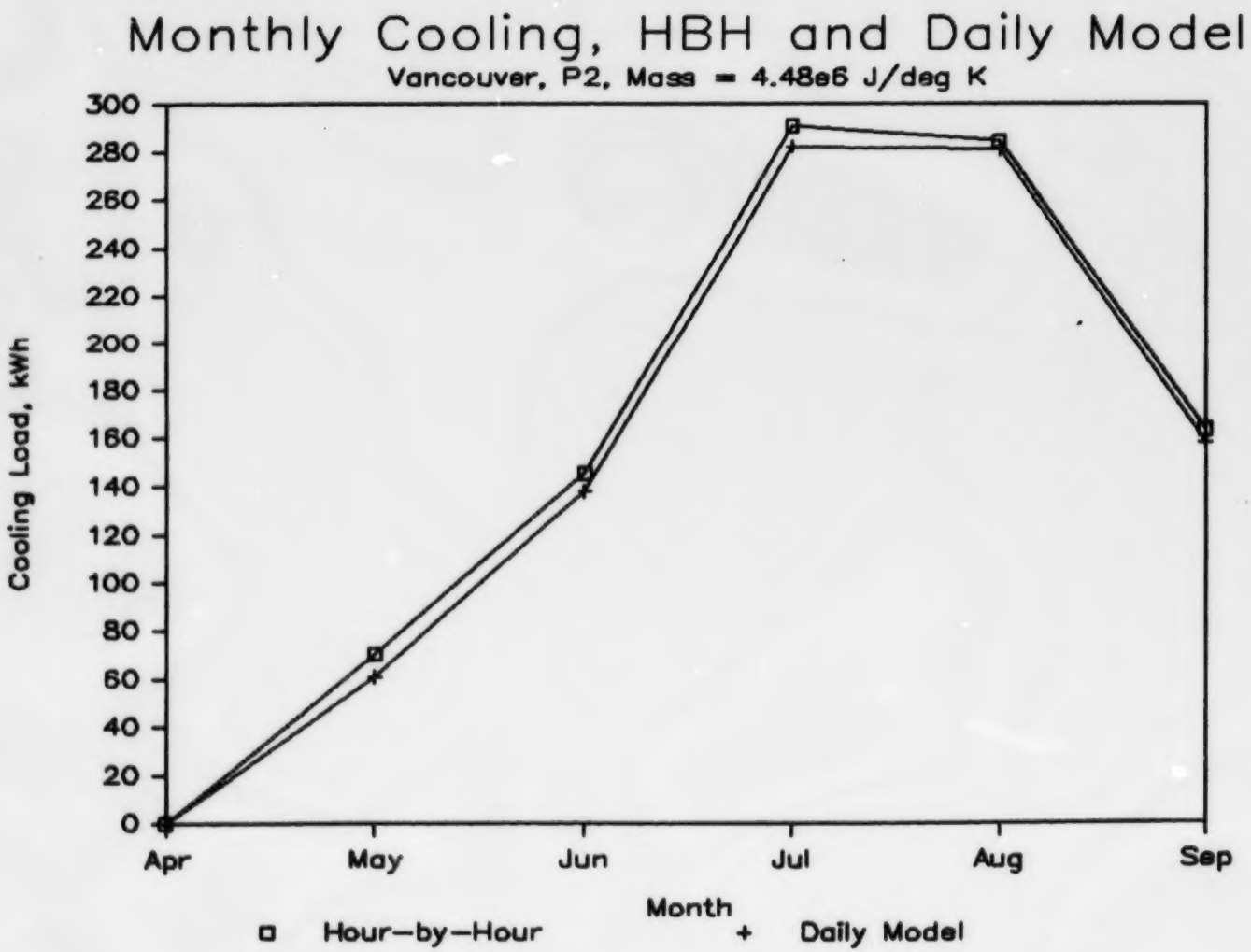

Monthly Cooling, HBH and Daily Model
Vancouver, P2, Mass = 4.48e6 J/deg K
Cooling Load, kWh
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
Apr
May
Jun
Jul
Aug
Sep
Month
Hour-by-Hour
Daily Model

Figure 2.6

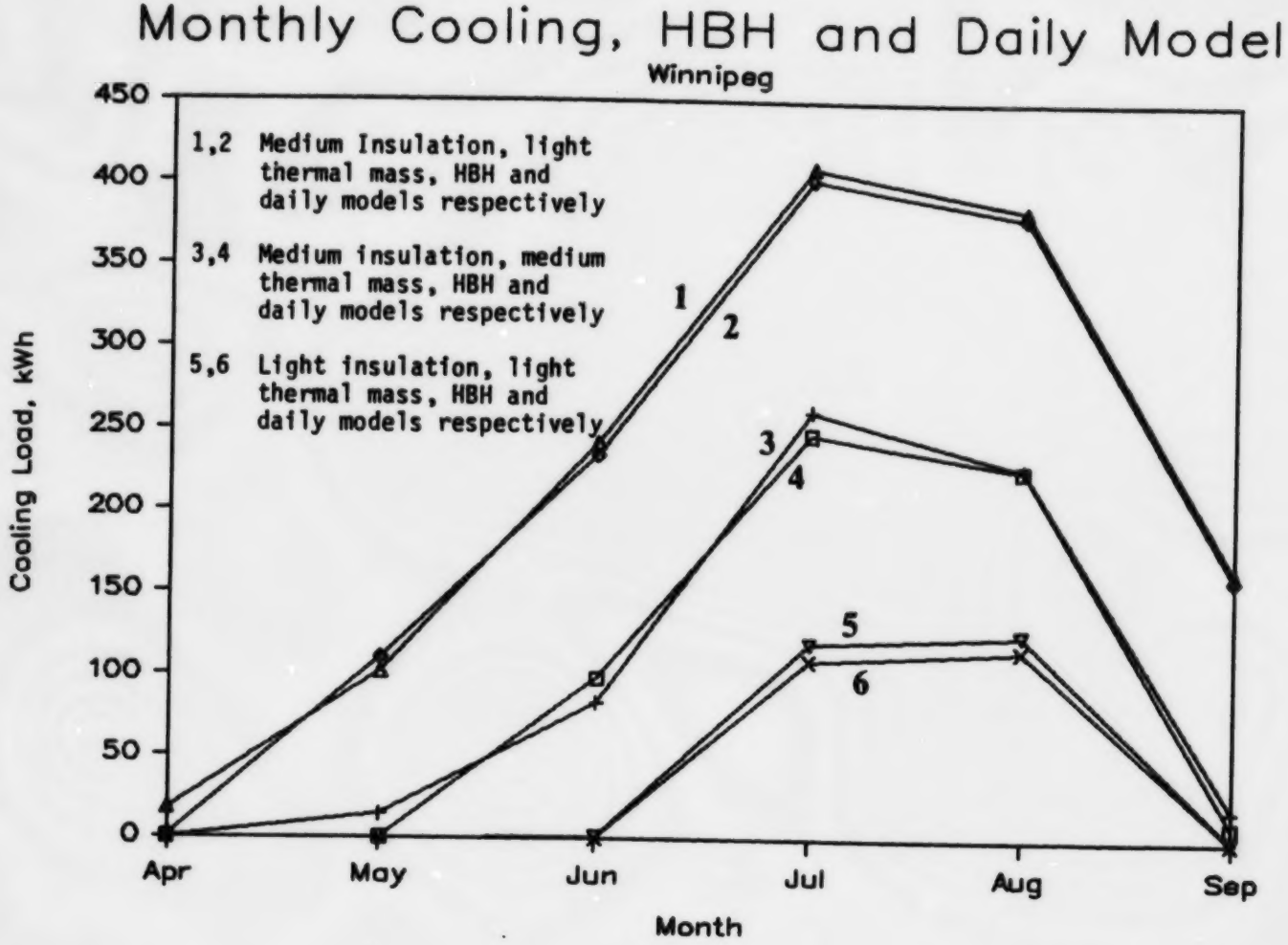

Monthly Cooling, HBH and Daily Model
Winnipeg
1,2 Medium Insulation, light thermal mass, HBH and daily models respectively
3,4 Medium insulation, medium thermal mass, HBH and daily models respectively
5,6 Light insulation, light thermal mass, HBH and daily models respectively
Cooling Load, kWh
450
400
350
300
250
200
150
100
50
0
Apr
May
Jun
Jul
Aug
Sep
Month
1
2
3
4
5
6

Figure 2.7

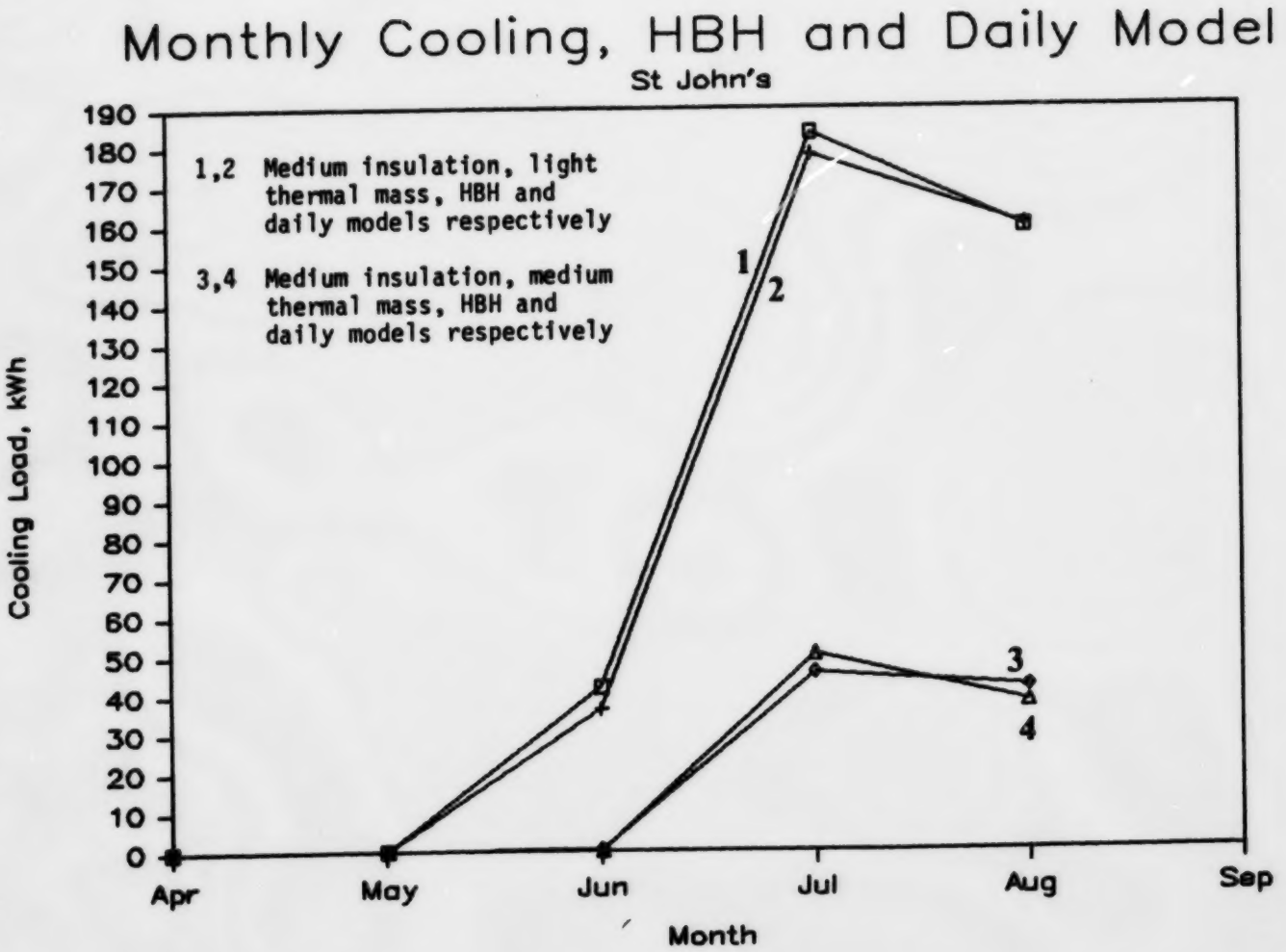

Monthly Cooling, HBH and Daily Model
St John's
1,2 Medium insulation, light thermal mass, HBH and daily models respectively
3,4 Medium insulation, medium thermal mass, HBH and daily models respectively
Cooling Load, kWh
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Apr
May
Jun
Jul
Aug
Sep
Month
1
2
3
4

Figure 2.8

Table 2.2

Cooling Load: BLAST, Daily and Hour-by-Hour Models

| | Cooling Load (kWh) | | |
|---|---|---|---|
| Month | BLAST | Daily | HBH |
| 4 | 3.01 | 11.31 | 2.39 |
| 5 | 16.4 | 0.00 | 12.45 |
| 6 | 107.1 | 82.96 | 97.86 |
| 7 | 190.1 | 169.25 | 178.90 |
| 8 | 124.6 | 114.05 | 118.00 |
| 9 | 23.4 | 22.09 | 20.41 |

The test house was simulated in an Edmonton, Alberta climate.It had a medium insulation level, and a thermal mass of 1.8 MJ/°K(0.037 MJ/$m^2$°K).

Table 2.3

Cooling System On-Time: BLAST vs. HBH Model

| Month | BLAST | HBH |
|---|---|---|
| 4 | 15 | 9 |
| 5 | 95 | 62 |
| 6 | 247 | 204 |
| 7 | 310 | 310 |
| 8 | 247 | 199 |
| 9 | 66 | 47 |

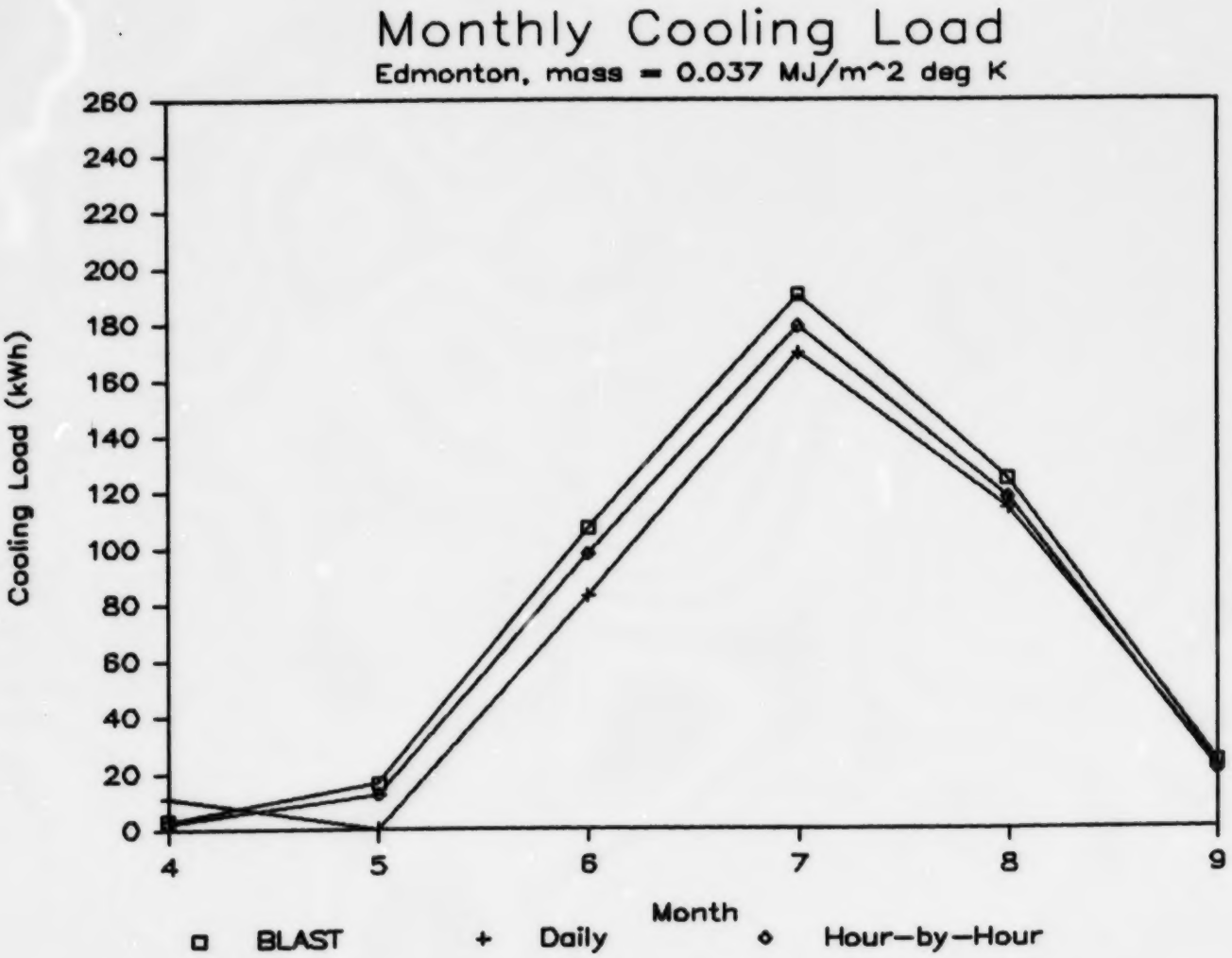

Monthly Cooling Load
Edmonton, mass = 0.037 MJ/m^2 deg K
Cooling Load (kWh)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
4
5
6
7
8
9
Month
BLAST
Daily
Hour-by-Hour

Figure 2.9

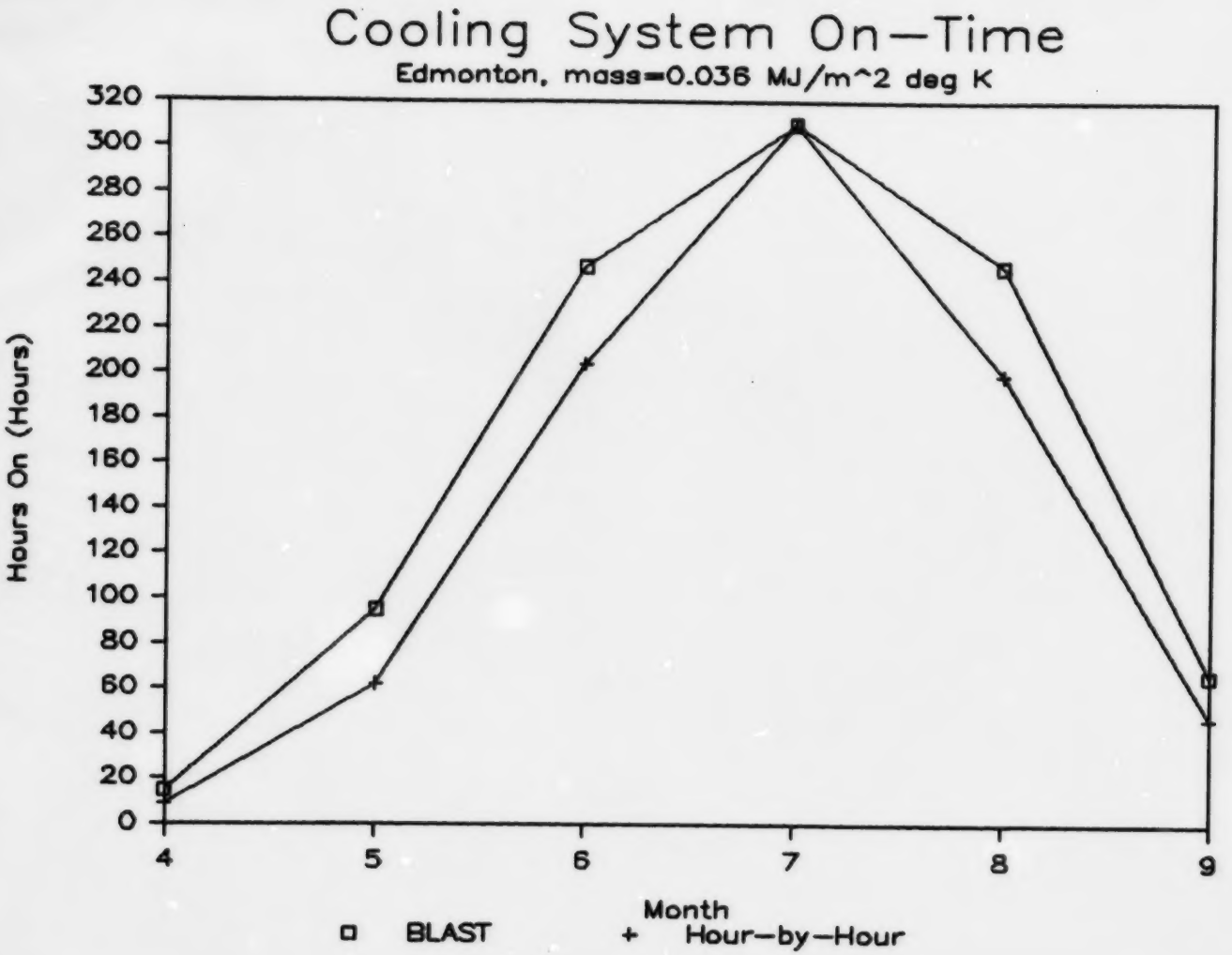

Cooling System On—Time
Edmonton, mass=0.036 MJ/m^2 deg K
Hours On (Hours)
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
4
5
6
7
8
9
Month
BLAST
Hour—by—Hour

Figure 2.10

# 3.0 WES SHADING MODEL

## 3.1 Introduction

The HOTCAN program's primary purpose has been to calculate winter heating loads. Most solar gains in winter are through the south-facing windows, and the gains through the east and west-facing windows occur when the sun is so low in the sky that the shading effect of an overhang would be insignificant. Therefore HOTCAN has an algorithm for estimating the shading effects of overhangs on south-facing windows, but it does not have one for dealing with shading on east and west-facing windows.

Because permanent overhangs of the kind which might be used for shading in winter seldom extend below the top of the window, HOTCAN does not have a model for dealing with shading from overhangs which do extend lower.

These two deficiencies do not create a problem when analyzing net heating load during the winter. They would create a problem in the analysis of cooling load in summer. In summer, east and west window solar gains are substantial. Also, in summer, awnings are often used for shading and they extend below the top of a window, so that this geometry must be modeled both for south-facing windows and for east and west-facing windows.

## 3.2 Objectives

(a) To improve the south window shading model to include low overhangs.

(b) To develop a shading model for east and west windows.

## 3.3 Method

The solar heat gain through a window (Ref. 2) may be expressed as follows:

$$G = A * SC * I * X_{\alpha} * F_S * 0.87$$

where G = solar heat gain for average day of month (J)

A = glass area ($m^2$)

SC = shading coefficient for window relative to single pane double strength sheet glass

I = incident solar radiation ($J/m^2$) for the average day of the month

$X_{\alpha}$ = off-angle incidence correction factor for solar gain (net equal to 0.93)

$F_S$ = factor to account for shading from overhangs, awnings, etc.

0.87 = solar gain coefficient for a single pane of double strength sheet glass

### 3.3.1 Determination of Shading Factor $F_s$

The shading factor is defined as the ratio of the solar radiation ISH incident on the window with shading over a particular time period, to the solar radiation I incident on the same window without the shading over the same time period.

A subroutine was developed to calculate I and ISH from the hourly weather data. The weather file contained data corresponding to Local Solar Time (LST). First the LST was converted to apparent solar time (AST) with the help of the following relation (Ref. 3):

$$AST = LST * 60 + ET + 4(LSM - LON)$$

where: ET = Equation of time, minutes of time

LSM = Local standard time meridian, deg. of arc

LON = Local longitude, deg. of arc

4 = Minutes of time required for 1.0 degree rotation of earth

Then the sun's position in the sky for that hour was expressed in terms of solar altitude $\beta$ and the solar azimuth $\phi$ . These angles in turn depend on the local latitude L; the solar declination DELT(M), a function of the month; and the apparent solar time expressed as the Hour Angle H, where H = 0.25 x (Number of minutes from local solar noon), deg.

The following equation related $\beta$ and $\phi$ to the three angles mentioned above:

$$\sin\beta = \text{Cos L} * \text{Cos(DELT(M))} * \text{Cos H} + \text{SinL} * \text{sin(DELT(M))}$$

$$\text{Cos}\,\phi = (\sin\beta * \sin L - \text{sin(DELT(CM))})/(\cos\beta * \cos L)$$

The angle of incidence, $\Theta$ for any surface was defined as the angle between the incoming solar rays and a line normal to that surface. The angle of incidence $\Theta$ was related to $\beta$, surface-solar azimuth $\gamma$ , and the tilt angle of the surface from the horizontal $\Sigma$ by:

$$\cos\Theta = \cos\beta * \cos\gamma * \sin\Sigma + \sin\beta * \cos\Sigma$$

Note that $\Sigma = \pi/2$ radians for a vertical surface and $\gamma = \phi$ for a south-facing surface. For an east-facing surface, the surface-solar azimuth angle, $\gamma = |\phi - (\pi/2)|$ in the morning.

Hourly weather data was available which contained direct normal (IB) and sky diffuse (ID) solar radiation data. The average hourly intensity of solar radiation incident on a vertical surface in the absence of a shading device was determined by the following equation:

$$IH = IB \cos + ID * FSS + ITH * FSG * \rho$$

where: FSS = angle factor between the window surface and the sky (=0.5 for unshaded windows)

ITH = total radiation falling on the ground (= IB sin + ID)
FSG = angle factor between the window surface and the ground (=0.5 for unshaded windows)
$\rho$ = ground reflectance (assumed to be 0.25 for the summer months, March - October, and 0.65 for the winter months, November - February inclusive).

(Note that this model assumed isotropic distribution of sky-diffuse radiation).

The presence of a shading device reduces the total radiation incident on the window. This reduction is dependent on the orientation of the window, geometry of the shading device and hour of the day. Two different kinds of shading devices are shown in Figure 3.1.

The shadow cast on the window by the overhang was determined by the relation (Ref. 4):

$$A = X * \tan\beta / \cos\gamma$$

where: A = relative length of shading cast below the overhang (dimensionless)
X = relative length of the overhang (=X/H) (dimensionless) or extension ratio

The relationship for calculating the angle factors FSS and FSG were developed (see Appendix) and the final equation for the average hourly radiation ISHHR incident on a shaded window was expressed as follows:

$$ISHHR = IB * (1 + Y - A) * \cos\Theta + ID * FSS + ITH * \rho * FSG$$

where: 1 + Y - A = the fraction of the window height that remains unshaded

$$I = [3600/(30*10^6)] \sum_{1}^{30\ \text{days}} \sum_{0}^{23\ \text{hrs}} IHR \quad (MJ/m^2/day)$$

$$ISH = [3600/(30*10^6)] \sum_{1}^{30\ \text{days}} \sum_{0}^{23\ \text{hrs}} ISHHR \quad (MJ/m^2/day)$$

Finally, the shading factor for the shaded window for that month was calculated as follows:

$$F_s = (ISH/I)$$

## 3.4 Results

The method developed was applied with Winnipeg (Manitoba, Canada) 1976 hourly measured weather data. A combination of the following geometries was considered for the south window:

X/H = 0.25, 0.50, 0.75, 1.00

Y/H = -0.25, 0.00, 0.25, 0.50

(a total of 16 different geometries)

A combination of the following geometries was considered for the east window:

X/H = 0.125, 0.25, 0.375, 0.50

Y/H = -0.25, -0.125, 0.00, 0.125, 0.250, 0.375, 0.50

(a total of 28 different geometries)

Results obtained from a few of the above-mentioned geometries were plotted. The plots of monthly average daily solar radiation incident on the south window with and without the shading against the month of the year are shown in Figures 3.2(a) and 3.2(b). Similar plots for the east window are shown in Figures 3.4(a) - (f).

The shading factors obtained for a particular geometry for the 12 months were fitted to a curve (using the least squares method) to get a correlation. The correlation is of the power series type. Because solar noon zenith angle (LAT - DEC), is a function of the month, $F_s$ becomes a function of (LAT - DEC). Table 3.1 lists the coefficients of the power series for all the South window geometries. Similarly, Table 3.2 lists those coefficients for the East window. A bar chart comparison of $F_s$ obtained from WES program's shading model correlations and $F_s$ obtained from the Balcomb model used in HOTCAN (Ref. 5) can be seen in Figures 3.3(a) - (d) (for South windows). As stated earlier, the Balcomb model could only model south overhangs, so comparisons could not be made for west and east overhangs.

Since it was developed using data for only one location, the WES shading model was tested for Toronto, Ontario (Latitude 44°N) using hourly weather data for 1977 to ensure that it would provide accurate predictions in other locations. The shading factors $F_s$ obtained for four East window shading geometries using hourly simulation were compared with shading factors $F_s$ calculated by using the WES shading model correlations. The comparison is listed in Table 3.3. The largest deviation in the monthly values of $F_s$ was 5.7%, and the root mean square deviation was 2.2%.

## 3.5 Discussion

Figures 3.2(a) and 3.2(b) show the effect of negative and positive separation ratios on south window solar gains. In Figure 3.2(a), shading reduces the total incident radiation throughout the year substantially regardless of the depth of overhang. However, in the positive separation case, Figure 3.2(b) shows that the reduction is much larger during the summer months as compared to that in winter months.

From Figures 3.2(b) and 3.4(e), it can be seen that the same overhang geometries on south and east have different shading behavior. The overhang shading on the south window (X = 0.50) reduces the total incident radiation in the summer months by as much as 58% while the

Table 3.1

Curve Fit Numbers for the Effect of Window Overhang on Incident Solar Radiation on South Vertical Windows

$$F_s = B0 + B1*y + B2*y^2 + B3*y^3 + \ldots\ldots\ldots\ldots$$

where y = (LAT - DEC)/100

| PARAMETER | .B0. . . | .B1. . . . | B2. . . | .B3. . . . | B4. . . . | B5 |
|---|---|---|---|---|---|---|
| (Overhang, Y/H=-0.25) | | | | | | |
| X/H=0.25 | 3.274 | -28.526 | 113.280 | -217.058 | 204.800 | -76.404 |
| 0.50 | 2.588 | -15.0597 | 29.417 | -4.218 | -35.021 | 23.905 |
| 0.75 | -2.742 | 38.503 | -171.473 | 343.402 | -313.503 | 106.282 |
| 1.00 | -2.331 | 28.435 | -103.718 | 152.022 | -74.757 | -2.604 |
| (Overhang, Y/H=0.00) | | | | | | |
| X/H=0.25 | 3.201 | -27.340 | 112.448 | -220.686 | 212.444 | -80.638 |
| 0.50 | 6.596 | -63.175 | 248.115 | -470.703 | 440.925 | -163.711 |
| 0.75 | 0.825 | 7.815 | -81.043 | 242.407 | -291.445 | 125.072 |
| 1.00 | -3.195 | 43.650 | -193.113 | 382.607 | -341.443 | 111.470 |
| (Overhang, Y/H=0.25) | | | | | | |
| X/H=0.25 | 4.591 | -42.11 | 177.184 | -349.923 | 330.861 | -121.133 |
| 0.50 | 3.824 | -32.0474 | 115.903 | -191.742 | 152.702 | -48.191 |
| 0.75 | 8.813 | -81.896 | 305.370 | -551.456 | 495.781 | -178.772 |
| 1.00 | -0.415 | 23.609 | -154.769 | 402.340 | -453.368 | 187.284 |
| (Overhang, Y/H=0.50) | | | | | | |
| X/H=0.25 | 1.311 | -5.996 | 32.355 | -76.001 | 82.388 | -33.819 |
| 0.50 | 8.635 | -87.369 | 362.420 | -708.56 | 664.737 | -241.830 |
| 0.75 | 9.519 | -90.972 | 343.638 | -609.016 | 519.033 | -172.382 |
| | 1.968 | 1.1826 | -79.875 | 300.070 | -402.90 | 185.158 |

Table 3.2

Curve Fit Numbers for the Effect of Window Overhang on Incident Solar Radiation on East Vertical Windows

$F_s = B0 + B1*y + B2*y^2 + B3*y^3 + \ldots\ldots\ldots\ldots$

where y = (LAT - DEC)/100

| PARAMETER | .B0. . . | .B1. . . . | B2. . . | .B3. . . . | B4. . . . . | B5 |
|---|---|---|---|---|---|---|
| (Overhang, Y/H=-0.25) | | | | | | |
| X/H=0.125 | 0.3467 | 3.6908 | -14.2614 | 26.0366 | -22.293 | 7.1706 |
| 0.250 | 0.6746 | -1.4436 | 11.3817 | -34.7542 | 46.6413 | -22.797 |
| 0.375 | 0.6432 | -1.7038 | 12.3130 | -36.6407 | 49.0221 | -24.0152 |
| 0.500 | 0.7594 | -4.5743 | 29.0670 | -80.0334 | 101.4520 | -47.5062 |
| (Overhang, Y/H=-0.125) | | | | | | |
| X/H=0.125 | 0.9938 | -2.7632 | 14.3601 | -35.2087 | 41.2514 | -18.4160 |
| 0.250 | 1.4567 | -9.6802 | 48.0845 | -113.6858 | 128.9928 | -56.1494 |
| 0.375 | 1.8823 | -15.7247 | 76.1247 | -176.0647 | 196.1174 | -84.1027 |
| 0.500 | 1.6635 | -14.2777 | 71.7060 | -171.2314 | 196.0230 | -85.8872 |
| (Overhang, Y/H=0.00) | | | | | | |
| X/H=0.125 | 1.6453 | -9.0172 | 41.8809 | -93.4142 | 100.7020 | -41.9412 |
| 0.250 | 1.7701 | -12.2249 | 59.7887 | -139.6176 | 156.8032 | -67.6832 |
| 0.375 | 2.6342 | -23.4115 | 110.8880 | -251.8578 | 276.0956 | -116.8357 |
| 0.500 | 2.2898 | -20.0623 | 95.5839 | -218.7351 | 242.0830 | -103.3697 |
| (Overhang, Y/H=0.125) | | | | | | |
| X/H=0.125 | 1.5713 | -7.0826 | 31.7379 | -68.4623 | 71.5138 | -28.9793 |
| 0.250 | 1.5240 | -7.9347 | 38.2750 | -88.0505 | 97.5438 | -41.6286 |
| 0.375 | 2.1936 | -16.9979 | 80.7335 | -183.2898 | 200.5749 | -84.6982 |
| 0.500 | 2.6578 | -23.2331 | 108.6825 | -243.4569 | 263.4127 | -110.1813 |
| (Overhang, Y/H=0.250) | | | | | | |
| X/H=0.125 | 1.3574 | -44.1700 | 19.8595 | -42.8097 | 44.4892 | -17.8706 |
| 0.250 | 1.3133 | -46.7499 | 22.3210 | -51.1323 | 56.6963 | -24.3012 |
| 0.375 | 1.9254 | -12.9712 | 61.7066 | -140.2314 | 153.5062 | -64.8408 |
| 0.500 | 2.8512 | -24.5975 | 114.2692 | -254.3669 | 273.4394 | -113.7622 |
| (Overhang, Y/H=0.375) | | | | | | |
| X/H=0.125 | 1.1816 | -2.1088 | 8.7487 | -17.3342 | 16.4604 | -5.9770 |
| 0.250 | 1.0794 | -1.2202 | 4.7267 | -8.9949 | 8.7681 | -3.4768 |
| 0.375 | 1.7699 | -10.5974 | 50.5728 | -115.6279 | 127.4921 | -54.2844 |
| 0.500 | 2.4407 | -19.1470 | 89.2735 | -199.1549 | 214.2623 | -89.1371 |
| (Overhang, Y/H=0.500) | | | | | | |
| X/H=0.125 | 1.2453 | -2.8034 | 11.7604 | -23.4872 | 22.4649 | -8.2533 |
| 0.250 | 1.1207 | -1.7169 | 7.5138 | -15.9943 | 16.7411 | -6.8400 |
| 0.375 | 1.2711 | -4.3210 | 21.6870 | -52.0346 | 60.0561 | -26.6312 |
| 0.500 | 2.3756 | -17.8368 | 82.9529 | -185.3319 | 200.1253 | -83.6979 |

Table 3.3

Comparison of $\overline{F}_s$ Computed using Hourly Weather Data* and $F_s$ Calculated from the WES Shading Model Correlations (for East Window)

| | CASE 1 | | | 2 | | | 3 | | | 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X=0.25 | | Y=0.0 | X=0.50 | | Y=0.00 | X=0.25 | | Y=0.25 | X=0.50 | | Y=0.25 |
| MONTH | $F_s$ | $\overline{F}_s$ | % diff. | $F_s$ | $\overline{F}_s$ | % diff. | $F_s$ | $\overline{F}_s$ | %diff. | $F_s$ | $\overline{F}_s$ | % diff |
| 1 | 0.876 | 0.879 | 0.34 | 0.777 | 0.783 | 0.77 | 0.963 | 0.963 | 0.00 | 0.893 | 0.887 | -0.68 |
| 2 | 0.846 | 0.870 | 3.45 | 0.727 | 0.771 | 5.71 | 0.952 | 0.959 | 0.31 | 0.864 | 0.878 | 1.60 |
| 3 | 0.834 | 0.828 | -0.72 | 0.704 | 0.705 | 0.12 | 0.946 | 0.942 | -0.42 | 0.855 | 0.848 | -0.83 |
| 4 | 0.824 | 0.828 | 0.48 | 0.638 | 0.692 | 1.30 | 0.941 | 0.941 | 0.00 | 0.833 | 0.839 | 0.72 |
| 5 | 0.816 | 0.807 | -1.11 | 0.678 | 0.661 | -2.57 | 0.939 | 0.931 | -0.86 | 0.830 | 0.805 | -3.11 |
| 6 | 0.822 | 0.806 | -2.00 | 0.690 | 0.659 | -4.70 | 0.942 | 0.930 | -1.30 | 0.848 | 0.803 | -5.60 |
| 7 | 0.817 | 0.809 | -1.00 | 0.680 | 0.661 | -2.87 | 0.939 | 0.933 | -0.64 | 0.833 | 0.812 | -2.59 |
| 8 | 0.822 | 0.813 | -1.10 | 0.681 | 0.667 | -2.10 | 0.940 | 0.934 | -0.64 | 0.831 | 0.820 | -1.34 |
| 9 | 0.834 | 0.824 | -1.20 | 0.704 | 0.691 | -1.90 | 0.946 | 0.935 | -1.18 | 0.855 | 0.831 | -2.90 |
| 10 | 0.845 | 0.829 | -1.93 | 0.726 | 0.694 | -4.61 | 0.952 | 0.943 | -0.95 | 0.864 | 0.843 | -2.49 |
| 11 | 0.873 | 0.885 | 1.40 | 0.772 | 0.797 | 3.14 | 0.962 | 0.962 | 0.00 | 0.890 | 0.899 | 1.00 |
| 12 | 0.889 | 0.874 | -1.50 | 0.798 | 0.782 | -2.05 | 0.967 | 0.959 | -0.83 | 0.905 | 0.885 | -2.26 |

* Toronto '77 (LAT = 44°N)

reduction in winter months is as little as 4%. In the case of East-facing window, Figure 3.4(e), the percent reduction throughout the year is about constant at about 10%. However, this 10% reduction amounts to 4.25 $MJ/m^2$/day for the summer month (June) as compared to only 1.25 $MJ/m^2$/day for the winter month (January). It would therefore be definitely beneficial to have a fixed shading device on an east-facing window although a removable shading device would be preferable. Also, it can be observed that the most appropriate separation ratio is zero.

The shading factors for the south window calculated both by WES shading model and Balcomb's model compare very closely for the winter months, but for the summer months, the WES model underpredicts $F_s$ more than it does for the winter months (Figures 3.3(a) - 3.3(d)). This might be due to the fact that WES model uses ground reflectance of 0.25 for the summer months whereas Balcomb's model assumes a little higher value of reflectance (= 0.30).

Finally, to verify that the WES shading model correlation could be extended to other locations, shading factors were first computed from the Toronto hourly weather data 1977 (Latitude 44°N) and then from the WES shading model correlation. When the two are compared in Table 3, the % difference in the worst case is only 5.7%. Therefore the shading factor correlation developed in the WES shading model can be used to predict $F_s$ for other locations with confidence.

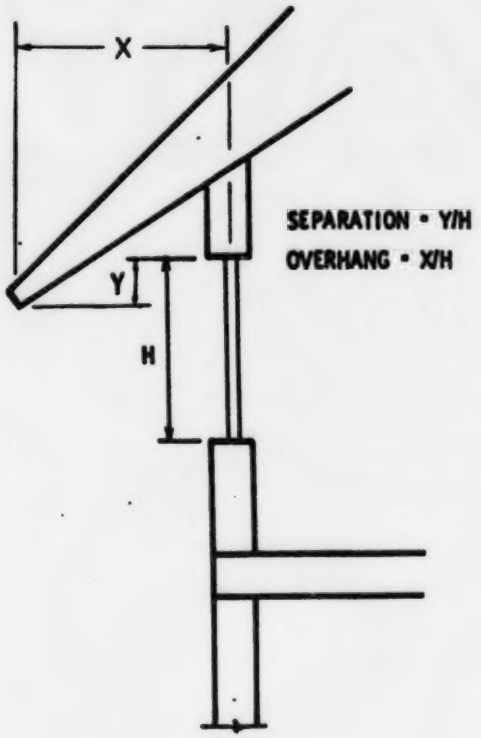



Figure 3.1(a) - Case of negative separation ratio.

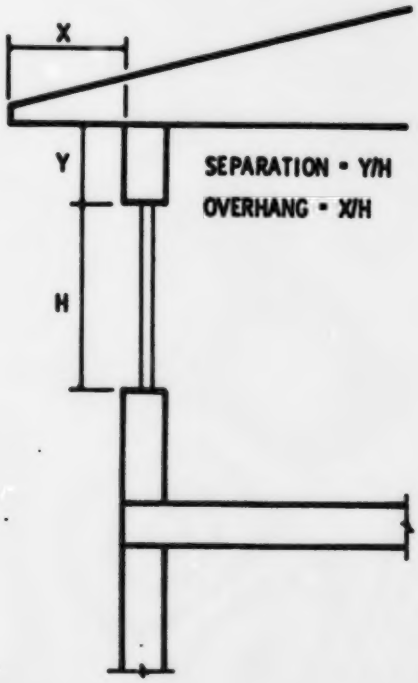



Figure 3.1(b) - Case of positive separation ratio.

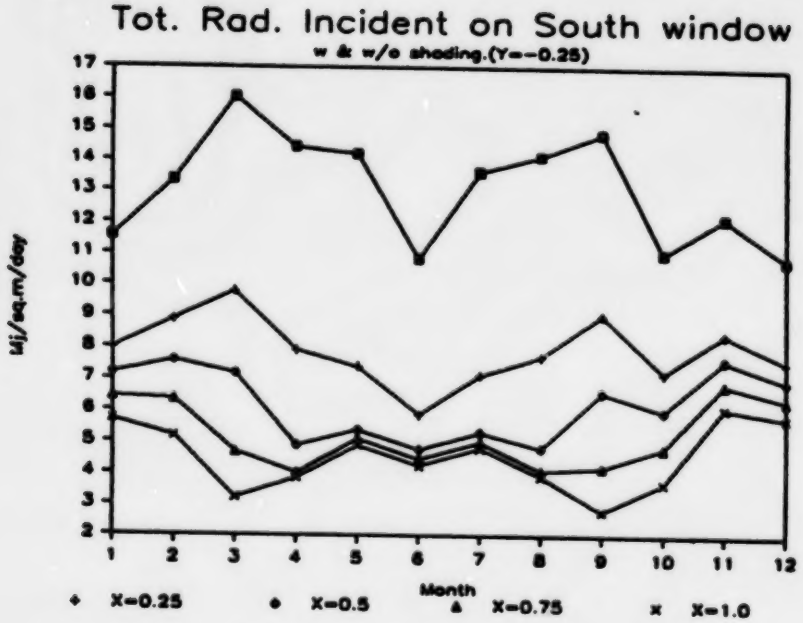



Figure 3.2(a) Total incident radiation on south window, Winnipeg (Latitude = 50°N), no overhang, Y = -0.25

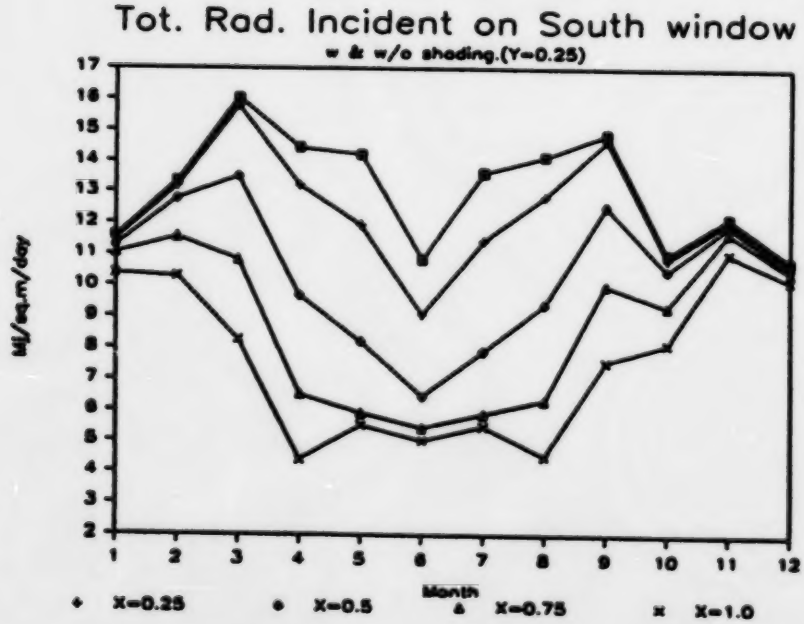



Figure 3.2(b) Total incident radiation on south window, Winnipeg, no overhang, Y=0.35.

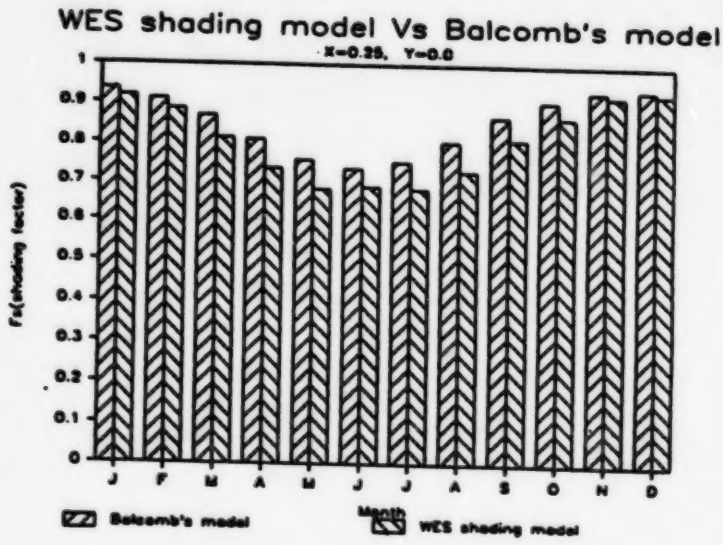



Figure 3.3(a)

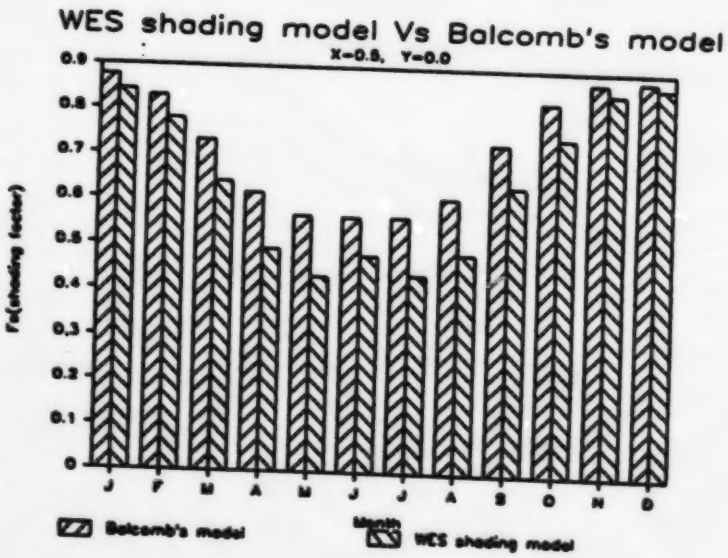



Figure 3.3(b)

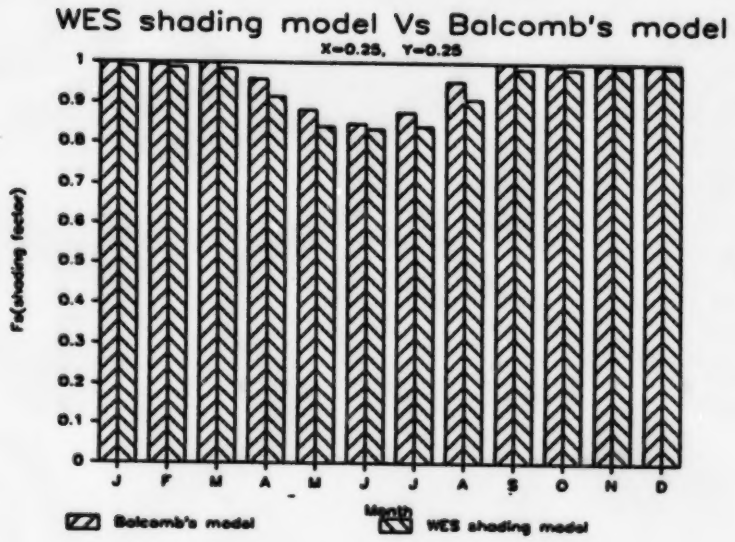



Figure 3.3(c)

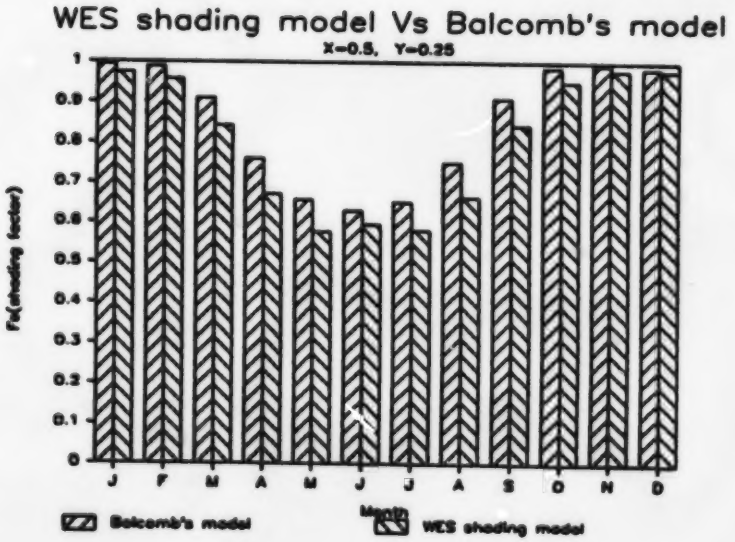



Figure 3.3(d)

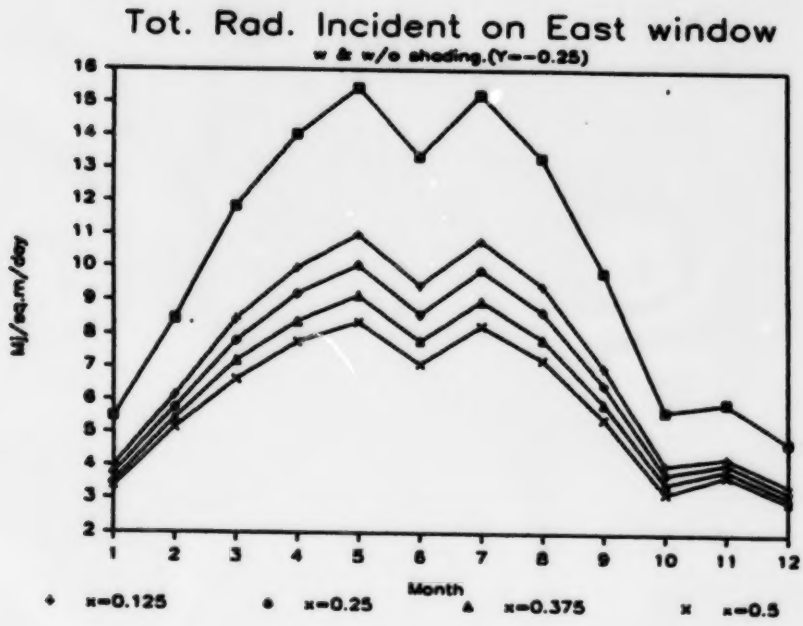



Figure 3.4(a) Winnipeg, east window, no overhang, Y = -0.25.

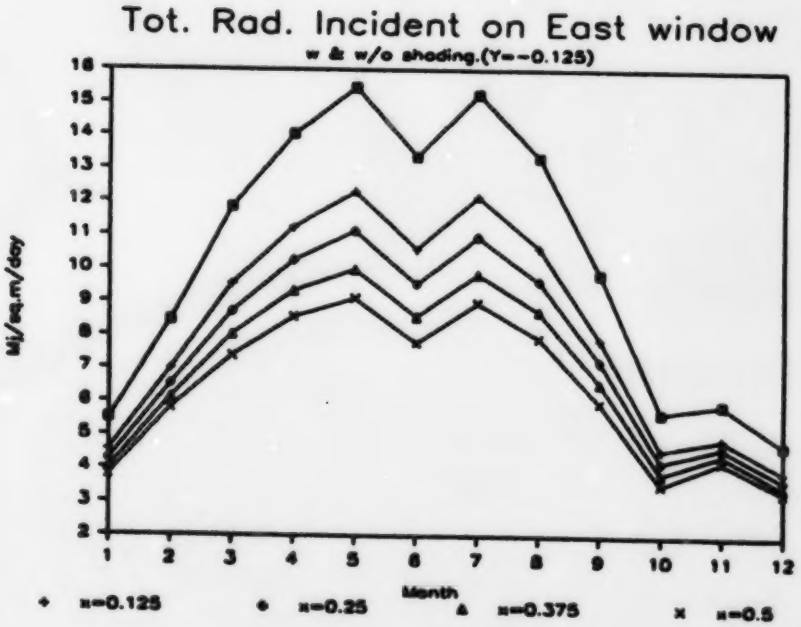



Figure 3.4(b) Winnipeg, east window, no overhang, Y = -0.125.

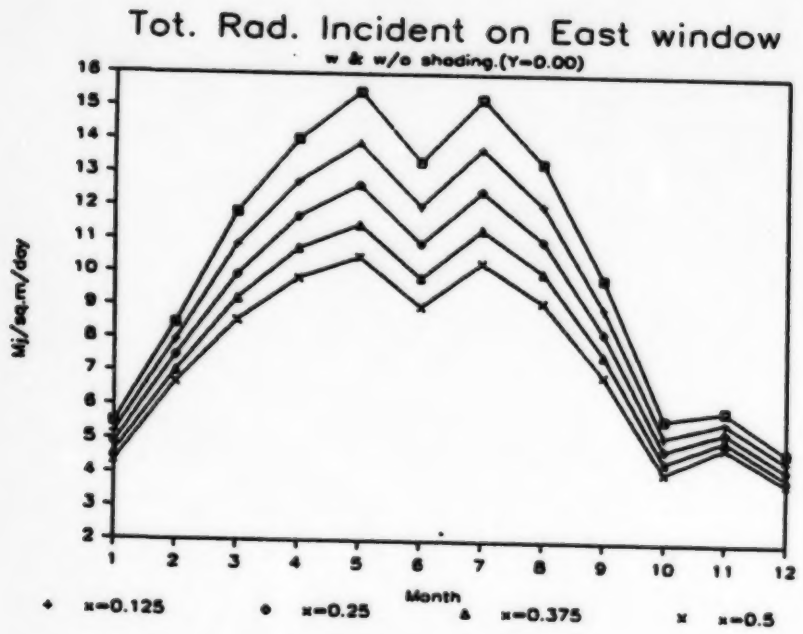



Figure 3.4(c) Winnipeg, east window, no overhang, Y = 0.00

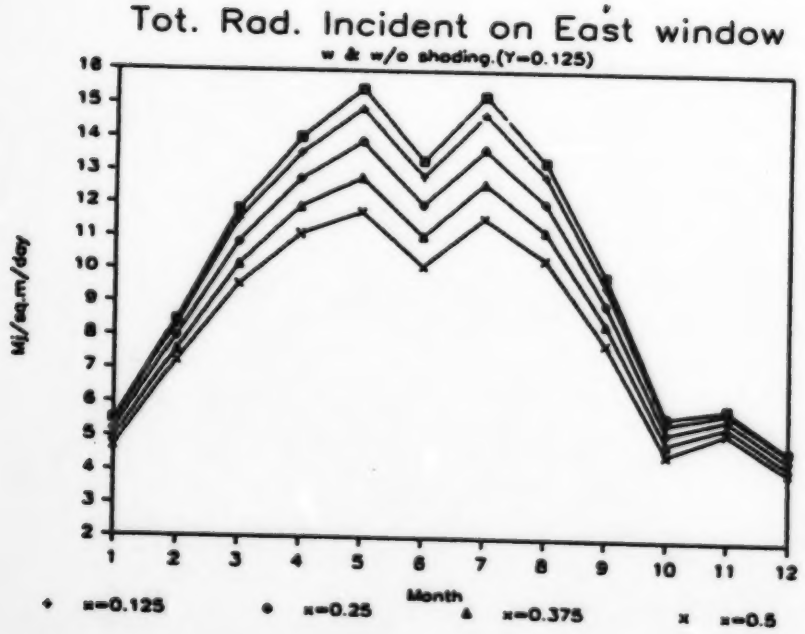



Figure 3.4(d) Winnipeg, east window, no overhang, Y = 0.125.

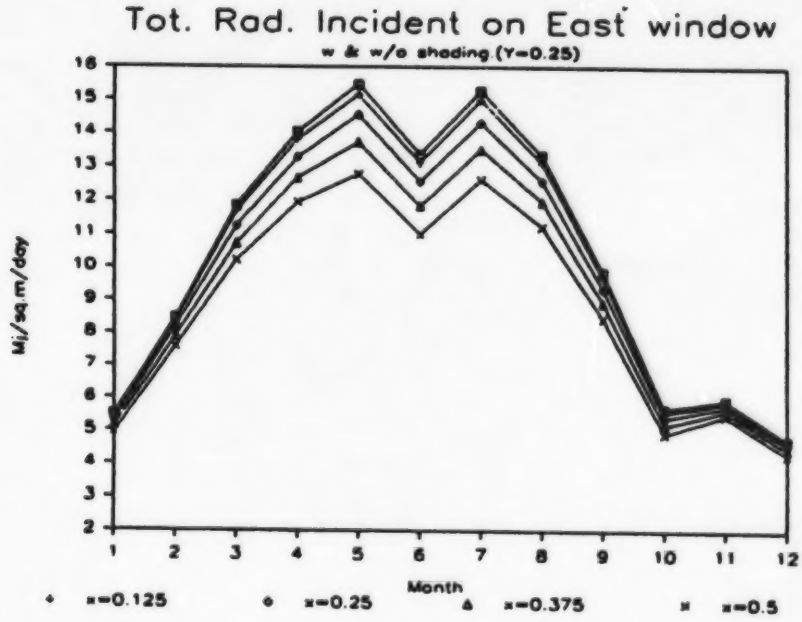



Figure 3.4(e) Winnipeg, east window, no overhang, Y = 0.25

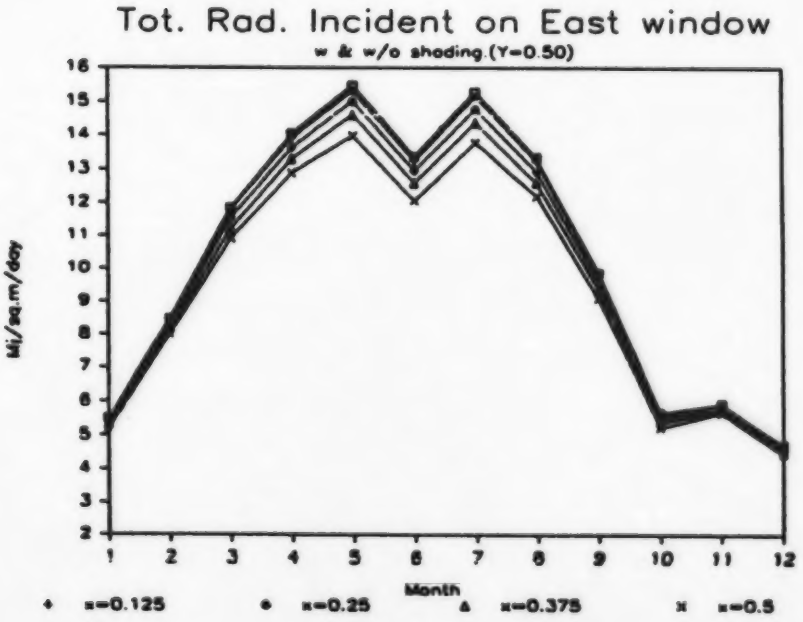



Figure 3.4(f) Winnipeg, east window, no overhang, Y = 0.50

## REFERENCES


1. Erbs, D.G.; Klein, S.A.; and Beckman, W.A. 1983. Estimation of Degree Days and Ambient Temperature Bin Data from Monthly Average Temperatures.

2. Dumont, R.S.; Lux, M.E. and Orr, H.W. 1982. HOTCAN: A computer program for estimating the space heating requirements of residences. National Research Council Canada.

3. ASHRAE Handbook 1981 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga. (pp. 172-279).

4. McQuiston, Faye C.; Parker, Jerald D. 1982. Heating, Ventilating and Air Conditioning, Analysis and Design, 2nd Edition. John Wiley and Sons.

5. Balcomb, D. J.; Barley, D.; Mcfarland, R.; Perry, Jr., J.; Wray, W.; Noll, S. 1980. Passive Solar Design Handbook. Los Alamos Scientific Laboratory, University of California.

6. Jones Jr., Robert E. 1980. "Effect of overhang shading of windows having arbitrary azimuth." Solar Energy, Vol. 24, Number 3, pp. 305 - 312.

7. Environment Canada. 1981. Canadian Climate Normals, Volume 1, Solar Radiation 1951 - 1980, Table 1, UDC: 551.521.12 (710).

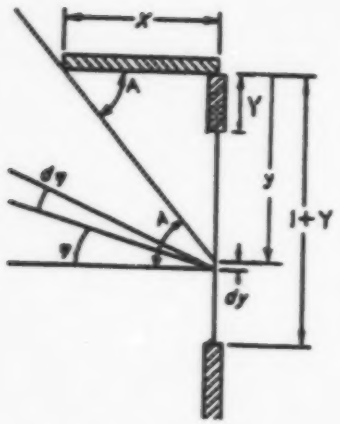
8. Duffie, J.A.; Beckman, W.A. 1980. Solar Engineering of Thermal Processes. John Wiley and Sons, Ltd.

9. Mitalas, G.P. 1982. "Basement Heat Loss Studies at DBR/NRC". National Research Council Canada. DBR Paper 1045, NRCC 10416, Ottawa.

10. G. K. Yuill and Associates Ltd. 1983. Verification of the BLAST Computer Program for Houses." BETT Publication No. 83.05, Energy, Mines and Resources Canada, Ottawa.

# APPENDIX A

## Development of Formulation for Angle Factor from Surface to Sky, FSS




Case (i) $y \geq 0$

Development of formulation for angle factor from surface to sky (Ref. 6) (FSS)

From Lamberti's cosine law in cylindrical coordinates, the fraction of the sky radiation which arrives at $\partial y$ from the differential angle $\partial\eta$ at an angle of incidence $\eta$ is given by $df = 1/2 \cos \eta \, d\eta$. Integration from $\eta = 0$ to $\eta = A$ yields the total unshaded fraction incident at dy as $f = 1/2 \sin A$. The average fractional diffuse insolation received by entire window is given by

$$[1/(y+1)] \int_{y=Y}^{y=1+Y} f\,dy = 1/2Y \int_{y=Y}^{y=1+Y} \sin A \, dy$$

but $A = \tan (y/X)$

Therefore,

$$FSS = (X/2)[(1/(\cos \tan^{-1}(1+Y)/X)) - (1/(\cos \tan^{-1}(Y/X))]$$

Angle factor from surface to ground FSG for $Y \geq 0$ is 0.5.

Case (ii) $Y < 0$

$$FSS = (X/2(1 - Y))[(1/(\cos(\tan^{-1}(1-Y)/X)) - 1)]$$

$$FSG = (2/\pi)*[(Y \tan^{-1}(X/Y)) + X/2 \ln(Y^2 + X^2) - X/2 \ln(X^2)]$$